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The Pilot Plant Installation at Queen's University for Studies of Atmospheric Fluidized-Bed Combustion

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THE PILOT PLANT INSTALLATION AT QUEEN'S UNIVERSITY FOR STUDIES OF ATMOSPHERIC FLUIDIZED-BED COMBUSTION

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SUMMARY

A pilot-plant atmospheric fluidized-bed combustor (AFBC) has been designed and installed at Queen's University. The combustion chamber, including both bed and freeboard, is 380 mm by 405 mm in cross-section (0.154 m^2 area) by 3.3 m high. The practical operating range of the bed height is about 0.2--1.0 m. The maximum fluidizing velocity is about 4 m/s. The maximum capacity for burning bituminous coal of normal quality (ash and moisture not unusually high) is about 100 kg/hr. The corresponding maximum combustion heat release rate is about 1.0 MW. Coal particles up to about 40 mm dia. can be fed. The combustor walls are refractory. Bed temperature is controlled by removing heat through in-bed cooling tubes, up to 48 in number (maximum cooling surface 0.9 m^2). Operation at bed temperatures up to about 1100 °C is permitted (a typical AFBC optimum running temperature is 850 °C). Limestone and other materials may be fed for SO_2 emission control. Coal and limestone may be fed in overbed or underbed modes, and solid residue may be removed from the top of the bed (by overflow) or from the bottom (by mechanical extraction). Product dust from the cyclone separator may be recycled to allow better carbon burnout. Systems are provided for gas and solids sampling from both bed and freeboard and for the analysis of these samples. A minicomputer serves needs in data acquisition and processing, a few process control functions, planning of experiments, and mathematical modelling of performance. Auxiliary systems include gas cooling and cleanup (heat exchangers, cyclone, baghouse) and solids handling and preparation (storage, transportation, mixing, screening). The pilot plant has been designed to accept a wide variety of possible fuels and operating modes and conditions. It will serve for basic research, the development of a data base on Canadian fuels and sulphur absorbents (principally limestones) to guide implementation of FBC technology in Canada, and as a vehicle for the advanced technical training of manpower for this new field.

1. INTRODUCTION

The primary objective of this report is to provide a description of the pilot plant facilities for the investigation of fluidized bed combustion which have been erected at Queen's University under contract with Supply and Services Canada, and under the sponsorship of Energy, Mines and Resources Canada. The introductory remarks below are divided into four subsections. The first, 1.1, sketches some salient features of fluidized-bed combustion processes. This material is primarily for the information of readers who are unfamiliar with the field, and it may be skipped by those who already know it well. The second, 1.2, summarizes the events and conditions leading to the present undertaking. The third relates the considerations leading to specification of the systems described herein and indicates the nature and scope of the activities to which the pilot plant may be applied. The last briefly describes the personnel involved.

1.1 Basic features of FBC

Fluidized bed combustion or "FBC" is quite simply a technique in which a fluidized bed of particles is used as a vehicle or medium for a combustion process. The particles themselves are not normally direct participants in the combustion reactions (i.e., the oxidation of combustible matter), but they may have important roles in reactions affecting air pollution, particularly in respect to sulphur dioxide. Typical bed materials are:

- ash, the mineral residue left by the burning of fuel
- mineral matter contaminating the fuel, such as clay, sand, and larger rock particles fed with unwashed or imperfectly washed coal. An extreme case is posed by the washery rejects from collieries; these contain as much as 50% combustible matter and are a possible FBC

fuel.

- o calcined and partly sulphated limestone, significantly when limestone is fed for sulphur dioxide emission control
- o sand, alumina particles, or other inert granular material fed in order to maintain a bed when suitable particles are not provided by other solid feed streams. This occurs, for instance, when coal is burned without limestone addition and the coal ash itself is too light to be retained (it is carried away by the gases).

The particle bed is contained in a combustion chamber which is normally of constant cross-section over the height of the bed. The walls may be refractory (ideally adiabatic) or cooled (then a significant part of the heat exchange system, receiving heat from the bed). The base of the chamber largely or wholly consists of a distributor plate through which air is admitted, either quite uniformly (as through porous plates of sintered metal or fritted quartz) or from a grid of localized sources (as through a "perforated plate" containing an array of orifices, or a plate fitted with an array of bubble caps). The air provided is the medium both for fluidization of the bed and for combustion of the fuel. We say "air" because it is by far the most common oxidant gas but other gases may, of course, be substituted; e.g., air enriched with oxygen.

The particle bed becomes fluidized when the flow of air is enough so that the bed is freely suspended in the gas stream rising through it. At this point, the pressure drop across the bed equals the weight of the bed per unit base area. The airflow employed in FBC, however, is normally well in excess of that required for the onset of fluidization. Gas-fluidized beds have the remarkable characteristic that such excess flow passes through the bed in a particle-lean phase. The bed exhibits a two-phase structure in which the dense phase has about the same voidage (or particle population density) as at the onset of fluidization. The

lean phase at first takes the form of bubbles rising through the dense phase which is continuous. At higher gas flowrates ("fluidizing velocities") and in deep enough beds (high enough ratio of bed height to bed diameter), slugging is observed--i.e., "bubbles" are formed that span the bed, at first high up in the bed and then lower down as well. At still higher gas flowrates, a state of "turbulent fluidization" is entered in which bubbles and slugs are poorly formed, continually distorted, quickly broken, and finally not even distinguishable. Solids and gas motion is increasingly chaotic, and the dense phase tends towards the discontinuous.

Under the conditions most favoured for practical fluidized-bed combustion, the bed is not deep (height is modest or small relative to diameter), the gas flow is further broken up by arrays of in-bed cooling tubes, and the particle size is too large to favour bubbling fluidization. The operation then generally tends towards turbulent fluidization.

A vigorous particle mixing is generally observed in bubbling and turbulent fluidization, but not in slugging. For this and other reasons, slugging operation is to be avoided. The good mixing observed under non-slugging conditions confers one of the great virtues of gas-fluidized beds as media for chemical reaction. The bed temperature is highly uniform and local hot spots are normally absent or quickly erased. Thus the bed may provide a means for conducting virtually isothermal reaction at the most favourable operating temperature. Some of the advantages of fluidized beds as media for combustion stem from this, but there are also others. Among the advantages that have been recognized are:

o under proper bed operating conditions, solid fuel

particles are plunged into an environment well above ignition temperatures and very rapidly and efficiently raised to the point of ignition. Thus ignition is swift and sure and combustion is exceptionally stable.

- combustion is, on the other hand, carried on at temperatures low enough so that nitrogen oxides formation from free (air) nitrogen is negligible
- almost any solid fuel can be handled, including many that could not easily be burned by other means (such as fuels with low or negligible volatile combustible matter, high ash, high moisture, high sulphur). The process is in fact quite extraordinarily versatile and forgiving in respect to acceptable fuel characteristics.
- compared to combustion in pulverized fuel flames, the needs for solid fuel preparation are minimal. Washing, drying and pulverization may all be entirely avoided. Only a relatively coarse crushing and grinding is normally required, or even desirable.
- by feeding limestone to the bed, sulphur dioxide can be quite innocuously removed at the point of generation, rather than later by environmentally and economically less desirable fluegas treatment processes. The product calcium sulphate (gypsum) is solid, reasonably inert, and potentially even useful.
- a major portion of the heat transfer to a working fluid can be effected through in-bed cooling surfaces. The heat transfer coefficient between the bed and such surfaces is exceptionally high, so total heat transfer surface is substantially reduced. The surfaces contacting the bed are well scoured and so not subject to fouling. A potential wear problem from abrasion is recognized, but the evidence indicates that this is not serious.
- maximum temperature levels (typically below 1000 °C) are far below those found in flame-based processes such as pulverized-fuel combustion in p.f. flames (up to near

2000 °C). Thus wear and danger to system components is greatly reduced.

- combustion intensity (burning rate per unit volume) is very high and heat transfer surface required is typically well below conventional processes. Total system size is thus dramatically reduced relative to hitherto conventional processes such as pulverized fuel combustion using p.f. flames. Substantial savings in volume of materials of construction are thereby afforded.

Many other advantages have been suggested. The attractions in terms of environmental protection, energy conservation, and a viable alternative to nuclear power have attracted commendation by environmentalists and conservationists. Amory Lovins, for example, has called FBC, "One of the most exciting clean fuel technologies we shall need for the coming energy transition". David D. Comey, President of [U.S.] Citizens for a Better Environment has said in regard to possible applications of FBC, "There is a major role for decentralized energy systems that can cleanly combust a variety of readily available fuels". Of course, the ultimate hazard of combustion, namely carbon dioxide increase in the atmosphere (with potentially severe climatic consequences), is in no way diminished, and in this respect, at least, nuclear energy is superior. At present these questions are under investigation and debate, and will remain so for years to come. Meanwhile, FBC in many ways offers the best means available for handling those hydrocarbon fuels that are still available in some abundance: coal, particularly in the lower grades, peat, and certain forest, municipal and industrial wastes and processing residues. Most processes for making liquid hydrocarbons from coal, peat and biomass, for example, produce large residues of char, usually with considerable sulphur content. These residues are presently often wasted or simply stockpiled, but they are potential FBC fuels and could

supply a substantial fraction, or even all, of the plant energy needs.

Certain salient features of FBC combustion processes stem from the basic nature of fluidized beds and make this mode of combustion vastly different from flame-based processes. The gas flowrate must be above the minimum required for fluidization. At the upper end, it must be below that which would blow the bed out of the combustor, unless provision is made for recirculation of particles. Processes using circulating beds have considerable potential for some applications but interest in the present work is restricted to non-recirculating systems, so the use of such very high gas flowrates is excluded. A system to be operated with high recirculation must be designed throughout as a circulating bed system, otherwise operation in this mode is not feasible.

The volumetric gas flowrate at bed temperature divided by the cross-sectional area of the bed is called the superficial gas velocity. In fluidization it is also commonly called the "fluidizing velocity". Since the gas characteristics in FBC are but little variable, the available range of fluidizing velocities is basically determined by the bed particle characteristics, particularly the particle size.

It is possible to run several fluidized beds in series and thus carry out combustion and heat transfer in stages. Our pilot plant system, however, like most systems presently under investigation or in use, is a single-stage system. Such systems are usually operated so that the bulk of the combustion takes place in the fluidized bed, the ideal objective being complete reaction to fully oxidized products (CO_2, H_2O). Ideally, too, solid fuel burns as fast as it is fed, so the amount of fuel in the bed (ranging from

fuel as fed to--in the final stage--char particles devoid of volatile matter) is ideally vanishingly small. The bed in practice thus consists almost entirely of non-combustible residues as described earlier in this section.

Operating bed temperature is constrained by material limits and reaction factors, most severely by minimum ignition temperature, ash softening and agglomeration, and--when limestone is applied for sulphur capture--by optimum limestone utilization. The extreme feasible temperature range is thus about 650--1100 °C, and for best operation it is usually considerably narrower. Optimum sulphur capture typically occurs around 850 °C, and this temperature is also often near the optimum in other respects.

In a system operated adiabatically, with near stoichiometric air supply and burning a good-quality coal, the theoretical combustion temperature is near 2000 °C. This is practically not allowable; bed particles and refractory walls obviously could not stand it, and there are other objections. It is thus normally necessary to extract heat from the bed or in some other way absorb some of the combustion heat release. There are basically two methods available:

1. Extract heat through cooling surfaces, typically cooled combustor walls and/or immersed cooling tubes.

2. Feed a material that absorbs heat, by increasing its sensible energy from the cold feed level to the bed operating level and/or by phase change (e.g., evaporation).

Operation with cooling through in-bed heat exchange surfaces is indicated when the primary object of combustion is to heat a working fluid, typically water or steam which may then be employed for such purposes as driving turbines,

process heating, and space heating. Dilution cooling, on the other hand, may be indicated when the object is to use the combustion product gases directly for such operations as agricultural drying; the combustor-product gases may then be greatly diluted with cold air, and it is natural to control the combustion temperature entirely through high excess air.

When the bed is operated with low excess air and temperature is controlled by in-bed cooling surfaces, as is the case in most practical applications, then a close proportionality exists between fuel feedrate, air feedrate, and cooling load. Airflow is then basically dictated by two considerations, namely quality of fluidization and system productivity, measured by burning rate per unit base area of the bed. Acceptable fluidizing velocities are typically 1--4 m/s. With operation near stoichiometric, at atmospheric pressure, and with temperature around 850 °C, this means that around 150--600 kg/hr m^2 of coal can be burned, combustion heat releases are 1.5--6 MW/m^2 and cooling loads are 1--4 MW/m^2. Since overall heat transfer coefficients typically vary relatively narrowly, cooling surfaces must be roughly proportional to the cooling load. A typical bed height is 1 m. Combustion intensities (heat release rates per unit of combustion chamber volume) are thus 1.5--6 MW/m^3. If 2 m^3 of freeboard space (empty gas space above the bed) are included, the intensity range drops to 0.5-2 MW/m^3.

Fluidized bed combustion can be carried out at pressures above atmospheric, practically up to around 10 atm. Combustion intensity is thereby substantially increased, combustor volume is correspondingly decreased, and the gases (after clean-up) can be used to drive a gas turbine, opening the possibility of efficient combined-cycle operation. However, the combustor must be encased in a pressure vessel and all the problems of solids feeding and

removal are greatly exacerbated.

It is clear from the above that several distinct modes of operation may be distinguished based on the following criteria:

- o operating pressure--atmospheric or elevated
- o bed retention--stable or circulating

Operation with a stable bed at atmospheric pressure is commonly referred to as atmospheric fluidized-bed combustion, AFBC. Operation with a stable bed at elevated pressure is called pressurized fluidized bed combustion, PFBC. Operation with circulating beds is presently being attempted only at atmospheric pressure, the volume of equipment that would have to be pressurized being considerably greater and of more complex shape.

1.2 Background to the present work

The first major programs of research and development on fluidized bed combustion or "FBC" were carried out in the United Kingdom in the 1960's and early 70's, mainly in the laboratories of the British Coal Board. Much of the pioneering work was done there and the research "cream" was skimmed off many of the problems in the sense of being there first, beginning the science, and developing the most obvious--and some not so obvious--ideas for practical application. The strong motivation came from Britain's then position of having no energy resource other than coal. The work drew attention to the benefits to be had from FBC, allowing clean and effective utilization of a wide range of solid fuels, including coals of every type and quality. In the latter half of the 70's, as concern over the increasing cost and coming exhaustion of conventional oil mounted and spread, R&D programs on FBC were inaugurated in many

countries of the world, including all the major industrial nations. In the U.S.A., the Energy Research and Development Agency (ERDA) was formed and quickly developed a major involvement in FBC. The Environmental Protection Agency (EPA) also entered in, seeing opportunities for abating SO_2 and NO_x emissions. In Canada, the major role in promoting and sponsoring FBC research and development was assumed by Energy, Mines and Resources Canada, particularly through the Energy Research Laboratories of CANMET.

Implementation of FBC is now well started. Some demonstration plants have been built and have already several years of operating experience. More are on the way. Some major vendors in the power and plant construction industries are offering FBC technology and various types of industrial apparatus have been built, mainly small in scale relative to major power generating stations, but working towards the larger sizes. The Peoples Republic of China has turned out to be a surprise early leader in industrial application; it was reported in 1980 at the Eighteenth Symposium (International) on Combustion that they have over 2000 operating installations, all of modest scale. In their case implementation was entered with very little prior research and development, and many of the systems are far from optimum in efficiency and pollution standards; however, they are facilitating the winning of energy from low-grade solid fuels.

With so many nations now involved, and with much initial basic R&D already done, it may be questioned how Canada can at this stage contribute to the technology and whether the effort can indeed produce anything worth the investment. A strong positive answer can be made, perhaps as follows. Canada has great resources of coal, peat and biomass. It also has enterprises such as tar sands processing and the forest industries which produce wastes or

residues that are further candidates for FBC fuels. Canada has also an abundance of limestones which can be used in FBC for sulphur dioxide emission control. Some of the coals in the Maritime Region have sulphur contents that are among the highest in the world. Lignite coals from the Prairies have other special problems which can be handled by FBC without much difficulty. In short, like most countries interested in FBC, Canada has its own peculiar stock of solid fuels and limestones whose special characteristics for FBC must be determined and considered in order to optimize the technology for domestic applications.

Further, no technology is ever perfect or static. The climb up the learning curve can usefully continue as long as the technology is used, and to ensure this advance, R&D should be appropriately employed throughout. Certainly, at this early stage of implementation, there are major improvements and innovations possible and much remains to be done.

Finally, since Canada clearly has in its fuel resources an abundance of those that are well suited to FBC and is thus likely to become a major user of FBC, it should develop its own industrial and R&D capabilities in this area. This development obviously includes the training and employment of people as well as the provision of facilities.

Interest in FBC in our laboratories at Queen's University is not recent. Work on fluidization dynamics on the one hand, and combustion of gaseous fuels and wood on the other, has been carried on since 1963. Work on FBC was started in 1973, beginning with that area--mathematical process simulation or modelling--in which contributions can be made with minimal investment and resources (Becker, Beer and Gibbs 1975). The central difficulty with experimental research in FBC is that realistic combustion studies cannot

be conducted on bench-scale apparatus. Pilot-scale operation must be entered if fluidization quality, combustion and heat transfer are to have the characteristics normal to the domain of practical application. Thus, while experimental work was desired almost immediately, as soon as the exercise in mathematical modelling identified the areas of greatest deficiency in physical knowledge, little could be done without funding at a much higher level than was readily available to university researchers in Canada in the early and mid 1970's. This stalemate was finally broken in 1979 by the present contract which was awarded by Supplies and Services Canada in response to our unsolicited proposal.

1.3 The conception, design principles, and purpose of the Queen's AFBC pilot plant

The pilot plant system proposed by us for studies of FBC in our laboratories was based on the following principal considerations:

1. Operation to be at atmospheric pressure. AFBC (atmospheric fluidized bed combustion) has wider application than PFBC (pressurized fluidized bed combustion), the system is simpler to build and operate, and it is considerably less expensive. Further, much of the information gained from AFBC is valid for PFBC as well. Hence, at this stage in our involvement--and Canada's, it was logical to choose an AFBC system. PFBC was seen as a costly but promising elaboration that might be considered later, and not necessarily for our laboratory. [Use of a circulating fluidized bed was not considered at all. It would involve a further elaboration and expense, and the system would certainly be beyond our ability to operate without a special building, a larger team of dedicated workers, and more elaborate auxiliary facilities.]

2. Combustor to be large enough to operate at realistic

bed depths, with realistic arrays of in-bed cooling tubes, and with realistic freeboard conditions and residence times

3. Plant to fit into existing laboratories in Dupuis Hall (the Chemical Engineering Building) and to operate with existing utilities (water, gas, high-pressure air, instrument air, electricity)

4. Provisions for feeding both solid fuel (coal immediately) and limestone, with underbed or overbed injection

5. Volumes of solid fuel, limestone, and solid residue ("ash") to be manageable in terms of volume and handling requirements

6. Provisions for bed level control

7. Provisions for flyash (cyclone product) recirculation

8. Fluidizing velocities up to 4 m/s

9. System to be fully instrumented so as to allow accurate and detailed performance studies

An initial program of pilot-plant studies to be performed was included in the proposal. First was a study of the combustion of high-sulphur New Brunswick coal with limestone application for sulphur removal. A program of parallel studies complementing and exploiting the pilot-plant work was also planned: mathematical modelling or simulation; cold-model investigations of fluidization quality, heat transfer and mass transfer; and basic studies of limestone reactivity and limestone/sulphur dioxide reactions in FBC.

When the contract was awarded in August, 1979 for building the pilot plant and bringing it into operation, the first step in implementation was the full design of the combustor. This was carried out in collaboration with scientists at the Canadian Combustion Research Laboratory, and most of the detailed planning of this unit was indeed done by Mr. Stefan Steindl of C.C.R.L. Two of the combustors were eventually built, one for the pilot plant at Queen's and one for a parallel facility at C.C.R.L. This arrangement allows the full pursuit of complementary or shared programs when wished, trading of experience, and reduction of costs. The equipment surrounding the combustor, however, is different at the two laboratories. The C.C.R.L. had considerable existing equipment and a more spacious and easily ventilated room. At Queen's, nearly everything had to be purchased or built; this slowed acquisition but helped in getting some modern and most appropriate systems.

The objectives which the Queen's pilot plant will particularly serve are considered to be as follows:

1. A vehicle for testing and characterizing fuels and SO_2 sorbents (mainly coals and limestones) for application in FBC, and providing necessary data for that purpose. Activities in this area will be planned to complement those of C.C.R.L.

2. A vehicle for testing and calibrating prediction methods based on bench-scale work and mathematical simulation. If these endeavours were to achieve complete success, the need for further pilot plant work would be eliminated altogether.

3. A vehicle for testing and developing instrumentation and equipment and testing operating techniques and

characteristics. Problems such as startup, equilibration, solids feeding, ash removal, flyash recycle, and shut-down can be usefully investigated. For instance, the success of a particular startup burner system has already been demonstrated and startup procedures have been developed. Corrosion testing is a long-term possibility (for the present, time is not available between other work for such lengthy and dedicated trials).

4. As part of the above and independently, a vehicle for investigating system response, optimization, and control of FBC systems

5. A vehicle for the training of personnel: engineers, scientists and technicians

The remainder of this report is taken up with a detailed description of the Queen's pilot plant facilities. Before proceeding to that, however, a few remarks are interjected below concerning the people who have been involved in the project, since it may be of some interest to note how such a relatively large and dedicated undertaking for a university has been staffed.

1.4 The Queen's AFBC team

The team involved in the subject contract consisted of Professors H.A. Becker, R.K. Code and J.T.N. Atkinson (the investigators), D. Liang (Engineer), and M. Couturier and F. Preto (Ph.D. students). Two undergraduate students were also employed as Summer Research Assistants. Dr. E.J. Anthony, of the Canadian Combustion Research Laboratory, was named the Scientific Authority by DSS/EMR.

Mr. Preto is basing his Ph.D. thesis research on the development of a full mathematical model. Data from

pilot plant studies are essential for testing and calibrating the model. He is also doing cold modelling studies relating to the development of submodels for heat and mass transfer. Ha is moreover a specialist in computing and is giving major help in the instrumentation and computerization of the pilot plant.

Mr. Couturier is particularly working on the reactions of sulphur dioxide and limestone in fluidized coal combustion. His results will help in the interpretation of the pilot plant data and further expand the capabilities of the mathematical model. He designed the gas analysis systems and probes for the pilot plant.

Mr. Liang is completing an M.Sc. degree part-time, with a thesis on turbulent flames. He is employed full-time as engineer on the FBC project and has been in charge of most aspects of construction and operation.

It is evident from the above that highly-trained people will be an important product of the project. Student interest in this area is indeed very high, and additional graduate students have been admitted and will be joining the project.

2. GENERAL FEATURES OF THE FBC RESEARCH FACILITIES

2.1 The pilot plant

A schematic diagram of the AFBC pilot plant is shown in Fig. 1. The combustor, physically an integral system, functionally consists of four sections:

1. The windbox, fed with blower air which then discharges through a distributor plate into the particle bed.

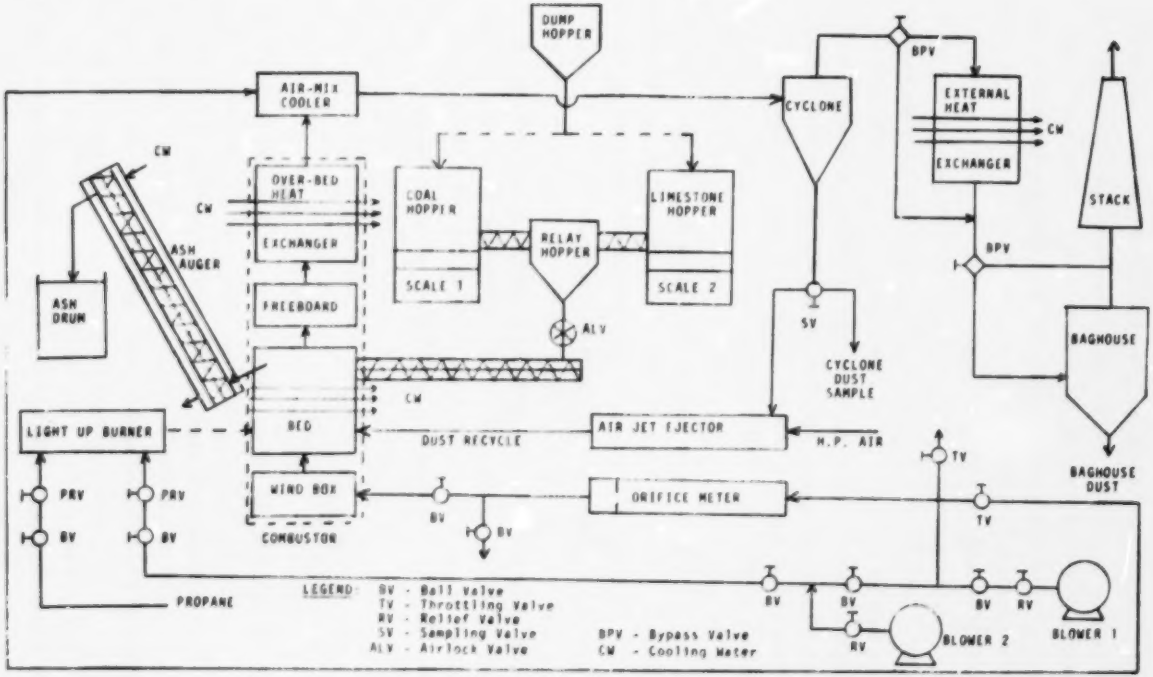


Fig. 1. Flowsheet of the AFBC pilot plant.

2. The particle bed, traversed by an array of in-bed heat-exchanger tubes carrying coolant. The coolant provided is city water. The amount of cooling surface can be varied by adding or removing in-bed heat-exchange tubes, and it is possible to operate with no tubes at all.

3. The freeboard, the gas space above the bed. This is a space where particles ejected from the bed may settle back into it and where gas-phase reactions are allowed time for greater completion.

4. The overbed heat exchanger, consisting of tubes traversing what might be regarded as the final section of the freeboard. The coolant is city water. Ideally, enough heat is extracted to drop the leaving gas temperature below the operating temperature limit of the cyclone separator.

To guard against the possibility of excess gas temperatures in the cyclone separator, an air-mix cooler is provided directly after the combustor and before the cyclone. Here blower air may be mixed with the combustor exhaust gas.

The cyclone separator removes all but the finest particles borne by the exhaust gases (the "flyash"). The product dust may be recycled to the bed or collected in a drum. A switching valve allows temporary diversion of the dust stream to a sample cup. Collection of sample over a suitable timed period allows determination of the dust recycle or collection rate.

The gases leaving the cyclone either flow through or bypass an outboard heat exchanger. The coolant is either fresh city water or the cooling water leaving the overbed heat exchanger, or a mixture of these two. The gas bypass and the cooling water flow are manipulated to produce an

appropriate gas temperature for baghouse operation.

The gas leaving the heat exchanger and/or its bypass is bypassed around the baghouse until the temperature has been appropriately adjusted as just described. The product dust from baghouse operation collects in a hopper at the bottom of the baghouse and is periodically removed.

The exhaust gases finally discharge to the atmosphere through a tall stack.

Coal and limestone arrive in barrels which are emptied through a dump hopper into the coal and limestone feed hoppers. In combustor operation, metering feeders move the coal and limestone from the feed hoppers into a relay hopper. They then drop into an airlock valve and pass through to a relay feeder which discharges into the bed. The relay feeder has provision for water injection, to moisten or wet the coal/limestone mixture, if desired. The relay hopper has an additional top feedport for hand-feeding. This feature is useful in combustor start-up, when a more highly reactive fuel may be preferable until a good operating bed temperature has been established.

Operation from a cold start cannot, of course, be established with solid fuel alone. Ignition temperature levels for continuation with solid fuel are achieved by means of a lightup burner which is connected to the combustor for this purpose. The bed is, in this process, lightly fluidized with blower air. Cooling water is provided to the in-bed heat exchange tubes. Combustion products of essentially adiabatic propane/air combustion discharge from the burner into the bed. When the bed has reached a suitable temperature level, feeding of solid fuel (either the fuel to be tested or a special starter fuel) is commenced. When the bed temperature is well above the ignition level,

the bed is momentarily slumped (all feeds are stopped) while the lightup burner is swiftly disconnected and the insertion port is sealed with a blind flange. Operation is then resumed.

The accumulation of solids in the bed is relieved by continuous removal. This also regulates the depth of the bed. Two mechanisms are provided. The first, a simple overflow port or drain in the combustor wall, allows operation at a single well regulated bed depth (about one metre, a practically likely value). The second, extraction from the bottom of the bed with the help of a helical conveyer, allows operation at any bed depth from the most shallow up to near the base of the overbed heat exchanger. However, this mode requires regulation of bed depth according to the pressure drop across the bed. The regulation thus possible is not nearly as good as by the overflow technique, but it is nevertheless usually acceptable.

The "ash" leaving the bed can be handled in two ways. It can be discharged directly, hot, into a sealed barrel or other container. Alternatively, it can be passed through a water-cooled auger (a gas/solids heat exchanger) and then collected in a barrel. The second approach is normally better: it quenches reaction, provides a cool product, and allows use of a larger vessel.

There are two entry ports provided for coal and limestone. One is at the bottom of the bed for underbed feeding. The other is just above the level of the overflow port, for overbed feeding at the "normal" operating bed depth. There are thus four possible overall modes of operation in respect to solids flow:

1. Overbed feed, overflow discharge
2. Underbed feed, overflow discharge

3. Overbed feed, underbed discharge
4. Underbed feed, underbed discharge

Two rotary blowers of nearly equal capacity are used for air supply. In startup, one is used to provide fluidizing air and the other supplies the lightup burner. When ignition has been established and the lightup burner has been removed, the two blowers can be paired to provide higher fluidizing velocities, if desired. Since turndown in speed of a rotary blower is limited (about 3:1 maximum), the availability of two equal machines in parallel also allows greater turndown (about 6:1) than a single one would permit. Further control, less elegant but acceptable, is however provided by bleeding air to the atmosphere through a throttling valve.

Both blowers are equipped with pressure relief valves. The lightup burner has a requirement for air at a fixed, sufficient pressure, but at a flow varying with the controlled demand. This is satisfied by running the blower serving the burner at more than sufficient capacity and letting the excess spill through the relief valve. This is perhaps not the most elegant solution, but it is simple, cheap, and quite satisfactory.

The coal and limestone feedrates are determined by continuous weighing of the feed hoppers, both of which rest on electronic weigh scales. The combustor air feedrate is determined with an orifice meter.

Thermocouples are provided at numerous locations for temperature measurement and/or performance monitoring. Ports are provided for gas and particle sampling. Thus very detailed information can be obtained about the combustor performance. Visual observations can be made through several viewing ports, two of which are provided with

sapphire windows in direct contact with the bed.

The complement of in-bed cooling tubes is variable, allowing variation of the cooling load. Cooling water flows are measured with rotameters, and the inlet and outlet water temperatures are recorded. Thus heat fluxes and overall heat transfer coefficients are determined.

The fuel and limestone dump hopper, Fig. 1, is located in the laboratory above the AFBC pilot plant laboratory. The cyclone, the outboard heat exchanger, and the coal and limestone feeders are on a mezzanine floor built around the combustor in the AFBC laboratory and reached by a staircase. The other equipment is at the pilot plant laboratory floor level. A view of the combustor, looking up towards the equipment on the mezzanine floor, is shown in Fig. 2.

2.2 Solids storage, handling and preparation

The solids storage and preparation facilities installed to serve the pilot plant consist of:

- 55 gal. steel barrels with quick-closing lids, for storage of fuel and limestone
- a trolley for moving barrels and a clamp for hoisting
- a particle separator, for separating fuel and limestone into fractions according to particle size
- an auger, for raising materials to the separator feed hopper from a floor-level dump hopper
- a cement mixer, for homogenizing the contents of a barrel
- an elevated hopper and crane, for dumping the contents of a barrel into the cement mixer.

The available crushing and grinding equipment is sufficient for preparing samples for analysis but not for

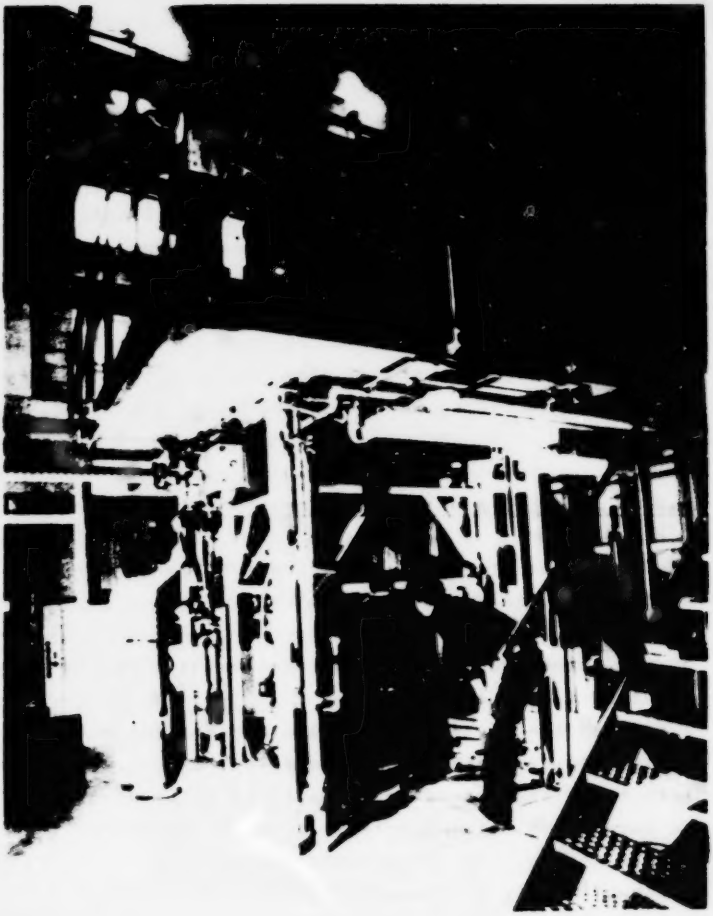


Fig. 2. The fluidized-bed combustor.

preparing much larger quantities of feed for the pilot plant. Fortunately there are in the vicinity of Kingston some sizable commercial quarrying operations, and their facilities (roll mills and screening plants) have been used for all the crushing required and for some size separation.

Views of the mixing facility and the solids screening (separating) facility are shown in Figs. 3 and 4.

2.3 Instrumentation and analysis systems

Probes were designed and built for gas sampling and particle sampling in the freeboard and in the bed. Sheathed thermocouples are installed at various locations in the combustor, the gas lines, and the cooling water circuits. Static pressures at various points in the bed and in the gas lines are sensed by a manometer bank and also by a differential pressure-transducer/scanning-valve system.

Results and computations have shown that the thermocouples in the freeboard are unreliable because of radiation error. An aspirating pyrometer probe is being built to replace these for reliable freeboard gas temperature measurement.

Provision has been made to connect all electronic sensors to a computer. The used PDP 11/10 minicomputer originally obtained (with funds outside the contract) has had a bad disk crash, is becoming unreliable, and is being replaced with Hewlett-Packard HP 9836A desk-top system. Besides indicating measured signals of pressure and temperature, the computer is programmed to convert the weight signals from the weigh scales into feedrates of fuel and limestone, and the pressure signals from the orifice meter into air flowrates. It forms suitable time-averages of signals, taking out fluctuations. It can be applied to

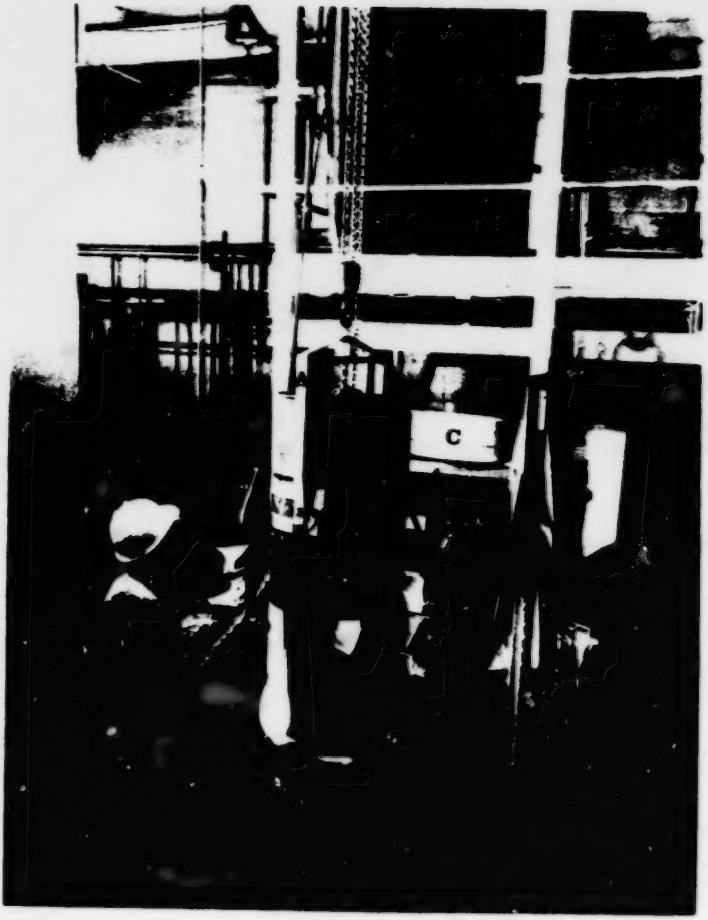


Fig. 3. The mixing facility (A, hoist; B, dump hopper; C, mixer).

Fig. 4. The solids screening facility (A, dump hopper; B, lift auger; C, feed hopper; D, Sweco screen separator).

automatic control of bed level by motorized underbed extraction of ash based on the pressure drop across the bed.

Gas analyses are done by a bank of single-species dedicated analyzers, all chosen for maximum resolution and minimum interference: paramagnetic detection for O_2, chemiluminescence for NO_x, and non-dispersive infrared for CO_2, CO, and SO_2. There is also an unburnt hydrocarbons analyzer which essentially measures carbon content of hydrocarbons in a gas and interprets it as methane.

A highly automated coal analyzer system is used to analyze fuels for moisture, volatiles and ash. An automated sulphur analyzer is used to determine the sulphur content of solids feeds and products. Atomic absorption and organic H/C/N analyzers are available for further solids analysis. A standard combustion calorimeter facilitates determination of calorific value.

2.4 Laboratory space and services

The pilot plant is located in a very convenient laboratory measuring 6.1 m by 7.3 m in floor area and 7.3 m in ceiling height. The main stack serving the building, over 15 m high, rises from one corner of this laboratory and takes the exhaust gases produced by the combustor. Extra ventilation is obtained through an exhaust fan placed in a window at ceiling level. A bridge crane just below the ceiling provides for the lifting of heavy equipment.

The laboratory directly above the pilot plant also serves the project. It has the same floor area, a 4 m ceiling height, and a break-through panel in the middle of the floor. The solids dump hopper (for filling the fuel and limestone feed hoppers) is located in the middle of this room and is fitted with a dust-collecting hood. Apart from

this, the room is set up as the solids analysis laboratory (moisture, volatiles, ash, sulphur and calorific value).

The pilot plant laboratory has built into one corner a small instrument room which houses the gas analysis systems and will also take the desk-top computer when it arrives.

The solids preparation systems (mixing, separation) are set up in the main Dupuis Hall "Chemical Engineering Pilot Plant Laboratory" which is on the same floor and just outside the FBC Pilot Plant Laboratory. The analytical screens for solids size analysis and the mills for preparing solids samples for analysis are located in the same area. Dust hoods followed by filters, all connected to a powerful exhaust system, are used to maintain clean air conditions around all units.

A room at the corner of the Chemical Engineering Pilot Plant Laboratory, diagonally opposite the FBC Pilot Plant Laboratory, has space for up to six desks and provides office space for the engineer and other workers. The Solids Analysis Laboratory has another two desks.

The laboratories are provided with 120 V and 208 V electrical service, 100 psig (high-pressure) and 15 psig (instrument) air, 40 psig propane, city water, vacuum and exhaust ducts connected to a high-capacity exhaust fan.

2.5 Safety systems and practices

The combustor is provided with appropriate explosion vents. One of the thermocouples in the bed is connected to a high-temperature alarm. A CO detector gives an alarm warning of dangerous room CO levels. Pipes are colour-coded and marked with standard markers. The light-up burner is

fitted with standard controls and meets all pertinent Ontario codes. All installations comply with the Ontario Health and Safety Act. Safety glasses, safety boots, and hard hats are required to be worn in all pilot plant operations.

3. DETAILS OF THE PILOT PLANT EQUIPMENT

3.1 The combustor

3.1.1 Overall features

The basic design features of the combustor, as noted earlier, were decided in consultation between our Queen's group and scientists at the C.C.R.L. The detailed design was done by Mr. Stefan Steindl of C.C.R.L., and the fabrication was by the firm of Trudel and McAdam in Ottawa.

The combustor is modular in construction. The lowest section, the windbox, hangs from the next section with its bottom about 150 mm above the floor. The distributor plate is mounted on top of it. Unbolting the windbox drops it to the floor, and it can then be slid out from under the combustor. The distributor plate is thus easily made accessible for attention, and the combustion chamber is also conveniently opened from the bottom for inspection.

The next five modules are identical in basic dimensions and construction except that the first is 737 mm high whereas the others are each 635 mm high. The chamber formed inside is like a brick-lined vertical flue. The chamber cross-section is 380 mm by 405 mm. The multiple brick lining consists of 114 mm of firebrick on the inside and 127 mm of high-density insulating brick on the outside. The brickwork of each module is encased by a mild steel shell

6.3 mm thick and flanged at top and bottom for bolting to the adjacent modules. The 30 mm space between the outside brick and the steel shell is filled with castable refractory. The outside casing dimensions are 935 mm by 960 mm.

The bottom member of these five modules differs at two opposite walls from the others in that these walls are open across the width of the combustion chamber. Panels that are water cooled on the outside and castable-refractory lined on the inside are installed in these openings. The panels contain a matrix of ports for the insertion of cooling tubes spanning the bed, in operation, in at one side and out at the other. There is provision for a maximum of 48 cooling tubes, with 57 mm distance between centers of adjacent tubes. The tubes are of 1/2 inch (21.3 mm O.D.) std. pipe. Ports not occupied by tubes are capped off; they can also be used for other purposes such as solids sampling, temperature and pressure probing, pneumatic solids recycle or injection, and solids extraction.

The other two walls of this module contain at centre bottom, on opposite sides, the ports for insertion of a light-up burner (port dia. 150 mm) and an underbed solids feeder (port dia. 150 mm). The port walls are of steel pipe with flanges on the outside.

3.1.2 The air distributor

The air required for combustion and fluidization is dispersed into the bed through 100 caps attached to a steel plate 380 mm square and 9.5 mm thick which forms the bottom of the combustion zone. The arrangement of the dispersion caps in a rectangular pitch, 38 mm by 35 mm, is shown in Fig. 5 and a photograph of an individual dispersion cap is

presented as Fig. 6. The dispersion caps were machined from stainless steel bolts 13 mm in diameter. An air passage 6.7 mm in diameter was drilled from the threaded end axially along the centerline to a point level with the bottom of the bolt head. Four injection ports with diameters of 3.2 mm located just under the bolthead and spaced at 90° intervals around the circumference of the bolt were then drilled to intersect the axial passage at right angles. The dispersion caps around the periphery of the array are used to attach the distributor plate to the windbox. The pressure drop across the dispersion caps is approximately 180 mm of water at a fluidizing velocity of 1 m/s. Location of the injection ports under the bolt heads shields the ports from the particle motion in the bed and reduces the loss of solids through the dispersion caps to the windbox. Injection of the air at a distance of 20 mm to 25 mm above the distributor plate provides an insulating layer of undisturbed solids for protection of the plate from the hign temperatures in the combustion zone.

3.1.3 The in-bed heat exchanger system

One measurement which is of primary interest in the evaluation of the operation of the combustor is the rate of heat transfer between the fluidized bed and an immersed bank of tubes through which a coolant is flowing. A complete evaluation covering a wide range of operating conditions requires a heat exchange system which may be readily modified as to: 1) the number of tubes (area available for heat transfer), 2) the geometric arrangement of the tubes, 3) the location of the tubes in the bed, and 4) the path of the coolant through the exchanger (number of passes).

In order to achieve this flexibility of operation the bed module was provided with two panels, containing 48 guide sleeves (I.D. 35 mm), on opposite sides of the

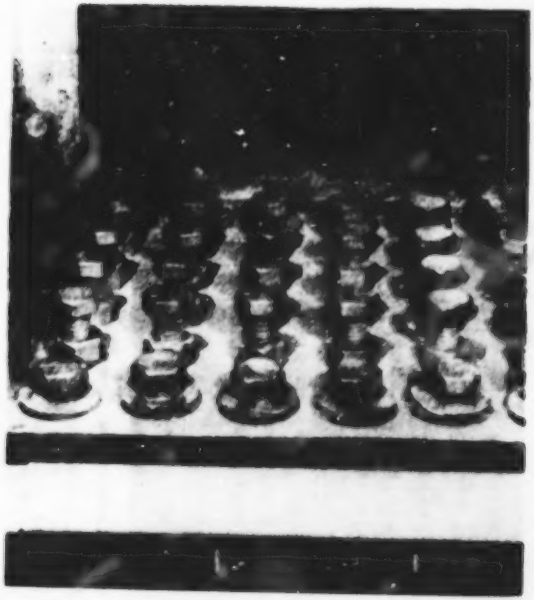


Fig. 5. The distributor plate showing the arrangement of the air dispersion caps.

Fig. 6. Individual dispersion cap.

combustor for the accommodation of a variable number of heat exchange tubes. A photograph of one of the panels is presented as Fig. 7. The outer surfaces of the panels are recessed 80 mm in order to reduce the distance that the guide sleeves and tube attachments project beyond the exterior surface of the combustor. The outer section of the panel, 550 mm high, 380 mm wide and 127 mm deep, is cooled by water flowing through the shell surrounding the guide sleeves. The inner shell surrounding the guide sleeves is filled with castable refractory to a depth of 75 mm to reduce heat losses to the outer shell. The tube bank of 1/2-in standard steel pipe (I.D. 15.8 mm; O.D. 21.3 mm) in a 57-mm rotated square-pitch arrangement spans the combustion zone, a distance of 380 mm. The tubes are sealed in the guide sleeves by O-rings. A tube attachment consists of a 1 1/4-in by 1-in reducing coupling threaded on to the guide sleeve followed by a 1-in by 1/2-in bushing in which the interior threads have been drilled out and a seat machined for an O-ring. The tube bundle is assembled by inserting the tubes through corresponding attachments on the two panels on opposite sides of the combustor. The flow circuit for the coolant is completed by attaching rubber hoses to the projecting ends of the tubes with gear clamps. The number of passes of the coolant through the exchanger may be changed readily by using short sections of hose as U-bend connectors as shown in Fig. 7. Guide sleeves unoccupied by tubes are capped. Unoccupied guide sleeves may be used as access ports. Two attachments for inserting sampling probes may be seen in Fig. 7. More guide sleeves have been provided in the design of the panels than are necessary to accommodate the number of tubes required by the heat load in the combustor. This flexibility permits an examination to be made of the effects of location and configuration of the tube bundle on the fluid mechanics and rates of heat transfer in the fluidized bed.

Fig. 7. The in-bed heat exchanger panel (A, U-bend connector; B, capped guide sleeve; C, attachment for sampling probe).

The cooling water flowrates are measured by a bank of shielded Fischer and Porter rotameters. The meters cover two ranges of flowrates depending upon the choice of float: 0 to 3.55 U.S. gal/min (224 cm^3/s) and 0 to 2.70 U.S. gal/min (170 cm^3/s). A photograph of the bank of rotameters is reproduced as Fig. 8. Taylor 'BI-THERM' (bimetallic) dial thermometers are provided for visual monitoring of the coolant temperatures. The cooling water temperatures are also measured by Type T (copper-constantan) thermocouples. Thermocouple outputs are measured by a Thermo Electric 'ELPH' indicator with digital readout in °C. The outputs may also be sampled by an Omega thermocouple scanner either manually or by the computer through an interface with the scanner.

3.1.4 The freeboard cooler and exhaust system

The upper sections of the combustor which project above the mezzanine are shown in Fig. 9. The two short sections at the top of the freeboard contain a crossflow, water-cooled heat exchanger. Each section, 120 mm high, contains a horizontal row of eight tubes of 1/2-in standard steel pipe (I.D. 15.8 mm; O.D. 21.3 mm) joined by 180° return bends to provide 8 passes for the cooling water. The flowrates and temperatures of the cooling water are measured by rotameters and Type T thermocouples as described for the in-bed exchanger.

The cooled gases leaving the exchanger are conveyed to the exhaust duct through the tapered section which is lined with refractory brick. Additional control of the temperature of the exhaust gases is provided by an air injector at the entrance to the exhaust duct. Two sources of dilution air are available for injection: high pressure laboratory air (550 kPa gauge) and blower air (34 kPa gauge). The injection of dilution air may also be used to

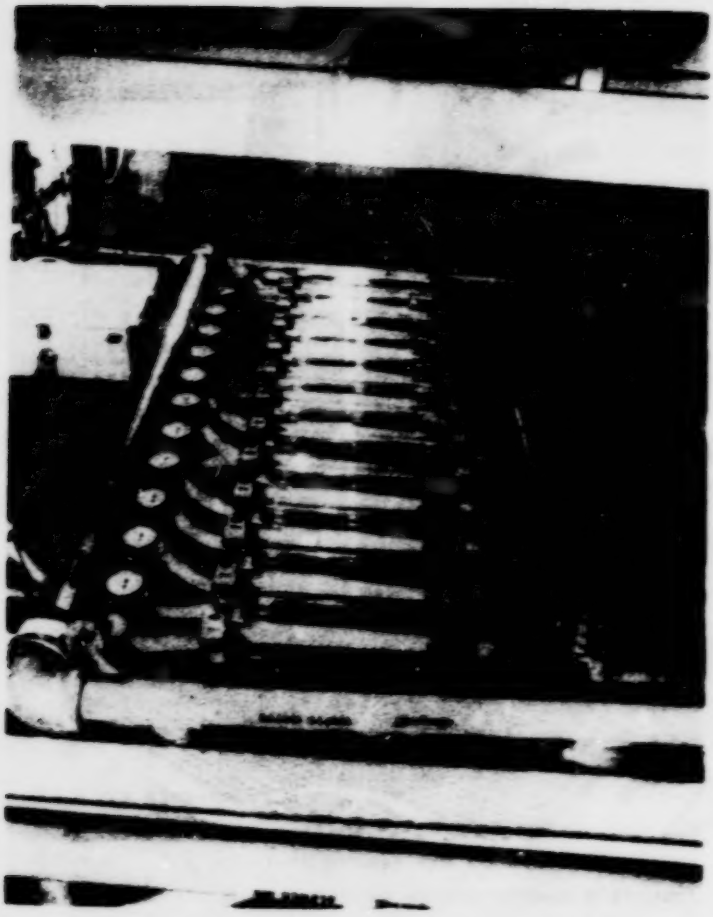


Fig. 8. Bank of rotameters.

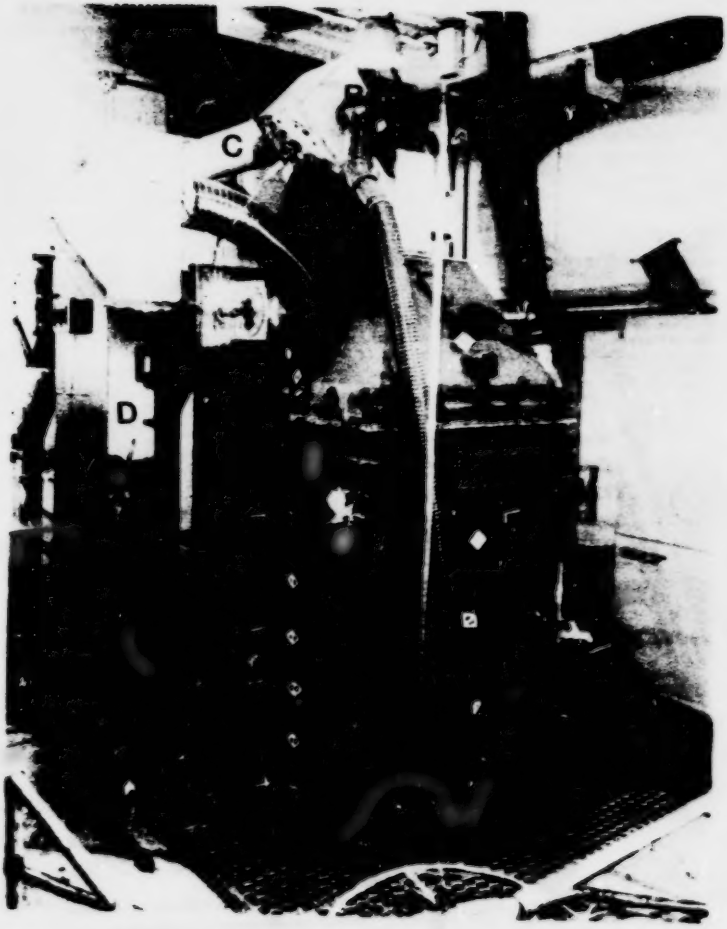


Fig. 9. Upper sections of the combustor (A, freeboard cooler; B, air injector; C, exhaust duct; D, cyclone separator).

improve the performance of the flyash collector when the bed is operated at low fluidization velocities (low flowrates of exhaust gases). The exhaust duct connecting the combustor to the next unit, the flyash collector or cyclone separator, is 200-mm, flexible, stainless steel, 'BENDWAY' tubing.

3.1.5 Access ports

Access ports have been provided for the introduction of the coal and limestone feed and the flyash recycle and for the removal of excess solids from the bed. Several viewing ports have been provided for visual observation of the fluidized bed. During startup of the combustor the mobile startup burner is attached temporarily to one of the underbed feedports. Additional ports are available over the full height of the combustor for monitoring the process. These include ports for temperature and pressure probes and probes for the removal of samples of gas and solids for chemical analysis. The locations of the ports, which are predominantly on two faces of the combustor, are shown schematically in Fig. 10 and Fig. 11. Table 1 summarizes the positions of the ports, identified in Fig. 10 and Fig. 11, in terms of vertical distance from the distributor plate and distance from the centerline of the combustor.

The temperature probes contain Type K (chromel-alumel) and Type T (copper-constantan) thermocouples depending upon the temperature level. The thermocouple outputs are sampled by an Omega thermocouple scanner either manually or by the computer through an interface with the scanner. The pressure probes are connected to water manometers for visual monitoring of the pressure at various levels in the combustor. A photograph of the manometer bank is shown in Fig. 12. The pressure lines may also be sampled by a 36-channel 'SCANIVALVE' scanner which connects individual lines to a pressure transducer. The pressure

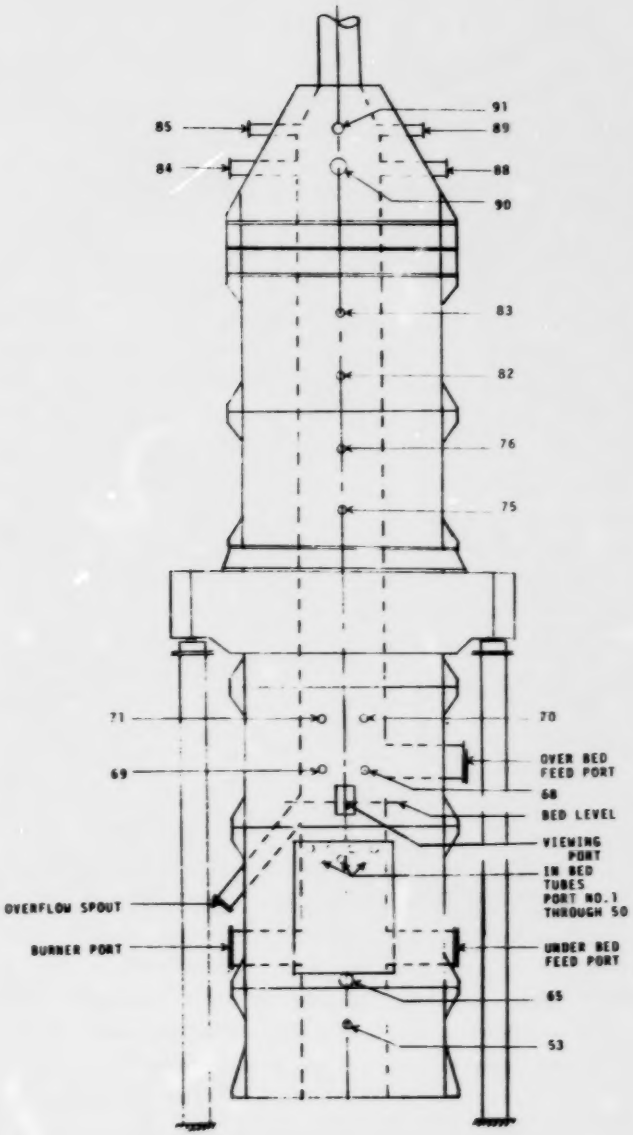


Fig. 10. Access ports, south face of combustor.

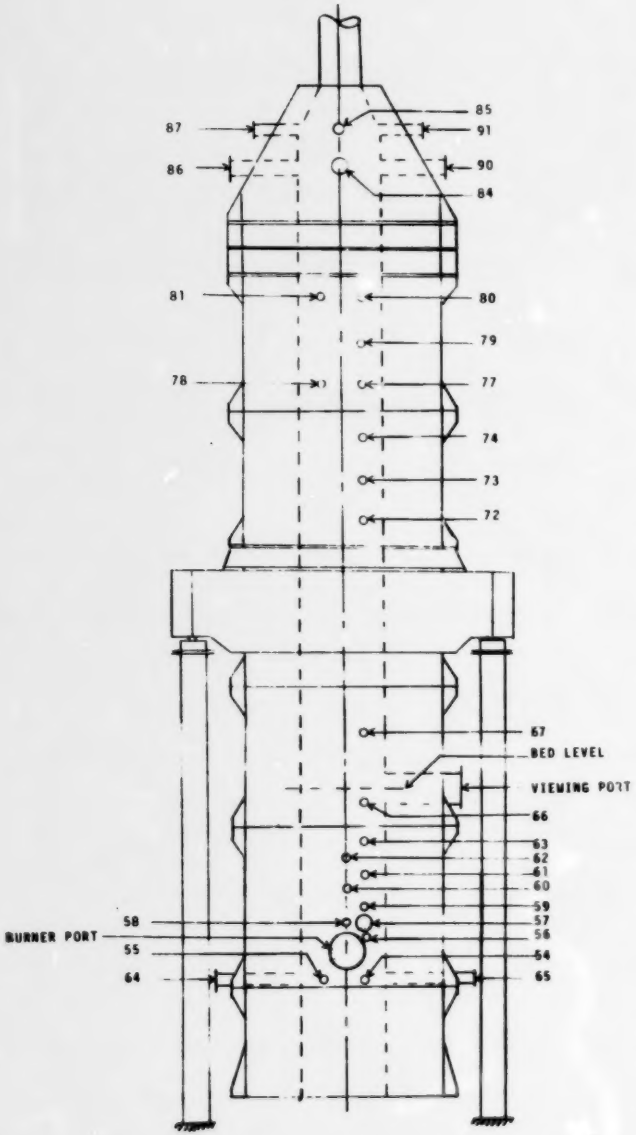


Fig. 11. Access ports, west face of combustor.

Table 1

Location of Access Ports

PORT NO.	DIA. (In)	REMARKS	LOCATION	VERTICAL * DISTANCE (cm)	OFF-CENTER DISTANCE (cm)
PORTS 1-50 ARE PART OF IN-BED HEAT EXCHANGER					
1	1 1/4	HEAT EXCHANGER	S1	15.	10.5
2	"	"	"	15.	2.
3	"	"	"	15.	6.
4	"	"	"	15.	14.5
5	"	"	"	19.	14.5
6	"	"	"	19.	6.
7	"	"	"	19.	2.
8	"	"	"	19.	10.5
9	"	"	"	23.	10.5
10	"	"	"	23.	2.
11	"	"	"	23.	6.
12	"	"	"	23.	14.5
13	"	"	"	27.5	14.5
14	"	"	"	27.5	6.
15	"	"	"	27.5	2.
16	"	"	"	27.5	10.5
17	"	"	"	31.5	10.5
18	"	"	"	31.5	2.
19	"	"	"	31.5	6.
20	"	"	"	31.5	14.5

PORT NO.	DIA. (In)	REMARKS	LOCATION	VERTICAL * DISTANCE (cm)	OFF-CENTER DISTANCE (cm)
21	1 1/4	HEAT EXCHANGER	S1	35.5	14.5
22	"	"	"	35.5	6.
23	"	"	"	35.5	2.
24	"	"	"	35.5	10.5
25	"	"	"	40.	10.5
26	"	"	"	40.	2.
27	"	"	"	40.	5.
28	"	"	"	40.	14.5
29	"	"	"	44.	14.5
30	"	"	"	44.	6.
31	"	"	"	44.	2.
32	"	"	"	44.	10.5
33	"	"	"	48.	10.5
34	"	"	"	48.	2.
35	"	"	"	48.	6.
36	"	"	"	48.	14.5
37	"	"	"	52.	14.5
38	"	"	"	52.	6.
39	"	"	"	52.	2.
40	"	"	"	52.	10.5

PORT NO.	DIA. (In)	REMARKS	LOCATION	VERTICAL * DISTANCE (cm)	OFF-CENTER DISTANCE (cm)
41	1 1/4	HEAT EXCHANGER	S1	56.5	10.5
42	"	"	"	56.5	2.
43	"	"	"	56.5	6.
44	"	"	"	56.5	14.5
45	"	"	"	60.5	14.5
46	"	"	"	60.5	6.
47	"	"	"	60.5	2.
48	1 1/4	HEAT EXCHANGER	"	60.5	10.5
49	-	HEAT EXCHANGER WATER JACKET	S1	-	-
50	-	HEAT EXCHANGER WATER JACKET	N1	-	-
PORTS 51-53 ARE UPSTREAM OF DISTRIBUTOR					
51	-	P/T UPSTREAM OF ORIFICE	ORIFICE PLATE	-	-
52	-	P/T DOWNSTREAM OF ORIFICE	ORIFICE PLATE	-	-
53	-	P/T WINDBOX	S0	-	-
PORTS 54-91 ARE FROM DISTRIBUTOR TO TOP OF FREEBOARD					
54	3/4	PRESSURE/TEMPERATURE	W1	5.5	9.
55	3/4	PRESSURE/TEMPERATURE	W1	5.5	9.
56	3/4	PRESSURE/TEMPERATURE	W1	20.	9.
57	2	SAMPLING	W1	28.5	9.
58	3/4	PROPANE BURNER CONTROL	W1	28.5	0
59	3/4	PRESSURE/TEMPERATURE	W1	36.5	9.
60	3/4	PRESSURE/TEMPERATURE	W1	44.5	0

PORT NO.	DIA. (in)	REMARKS	LOCATION	VERTICAL * DISTANCE (cm)	OFF-CENTER DISTANCE (cm)
61	3/4	PRESSURE/TEMPERATURE	W1	52.5	9.
62	3/4	PRESSURE/TEMPERATURE	W1	61.	0
63	3/4	PRESSURE/TEMPERATURE	W1	69.	9.
64	2	FINES RECYCLE	N1	5.	0
65	2	< >	S1	5.	0
66	3/4	PRESSURE/TEMPERATURE	W2	82.5	9.
67	3/4	PRESSURE/TEMPERATURE	W2	106.5	9.
68	3/4	SAMPLING	S2	100.5	10.
69	3/4	SAMPLING	S2	100.5	10.
70	3/4	SAMPLING	S2	131.	10.
71	3/4	SAMPLING	S2	131.	10.
72	3/4	PRESSURE/TEMPERATURE	W4	212.	9.
73	3/4	SAMPLING	W4	233.5	9.
74	3/4	PRESSURE/TEMPERATURE	W4	252.5	9.
75	3/4	SAMPLING	S4	217.	0
76	3/4	SAMPLING	S4	250.	0
77	3/4	PRESSURE/TEMPERATURE	W5	275.5	9.
78	3/4	SAMPLING	W5	275.3	9.
79	3/4	SAMPLING	W5	297.	9.
80	3/4	PRESSURE/TEMPERATURE	W5	319.	9.
81	3/4	SAMPLING	W5	319.	9.
82	3/4	SAMPLING	S5	280.5	0

PORT NO.	DIA. (in)	REMARKS	LOCATION	VERTICAL * DISTANCE (cm)	OFF-CENTER DISTANCE (cm)
83	3/4	SAMPLING	S5	313.5	0
PORTS 84-91 ARE DOWNSTREAM OF FREEBOARD (TOP) HEAT EXCHANGER					
84	2	< >	W6	372.	0
85	2	< >	W6	387.5	0
86	2	< >	N6	372.	0
87	3	< >	N6	387.5	0
88	2	< >	E6	372.	0
89	2	< >	E6	387.5	0
90	2	< >	S6	372.	0
91	3	< >	S6	387.5	0
PORTS 92-99 ARE IN GAS STREAM PAST FREEBOARD					
92	-	P/T AIR INJECTION BOX	-	-	-
93	-	P/T CYCLONE AIR OUTLET	-	-	-
94	-	P/T HEAT EXCHANGER INLET	-	-	-
95	-	P/T HEAT EXCHANGER OUTLET	-	-	-
96	-	P/T FABRIC FILTER BYPASS BOX	-	-	-
97	-	P/T FABRIC FILTER INLET	-	-	-
98	-	P/T FABRIC FILTER OUTLET	-	-	-
99	-	STACK GAS TEMPERATURE	-	-	-
100	-	<BED TEMP† PROBE (NO PORT)>	-	-	-
101 112		PORTS 101-112 MONITOR WATER TEMPERATURES ON MANOMETER BANK ON NORTH SIDE (LEFT TO RIGHT)			

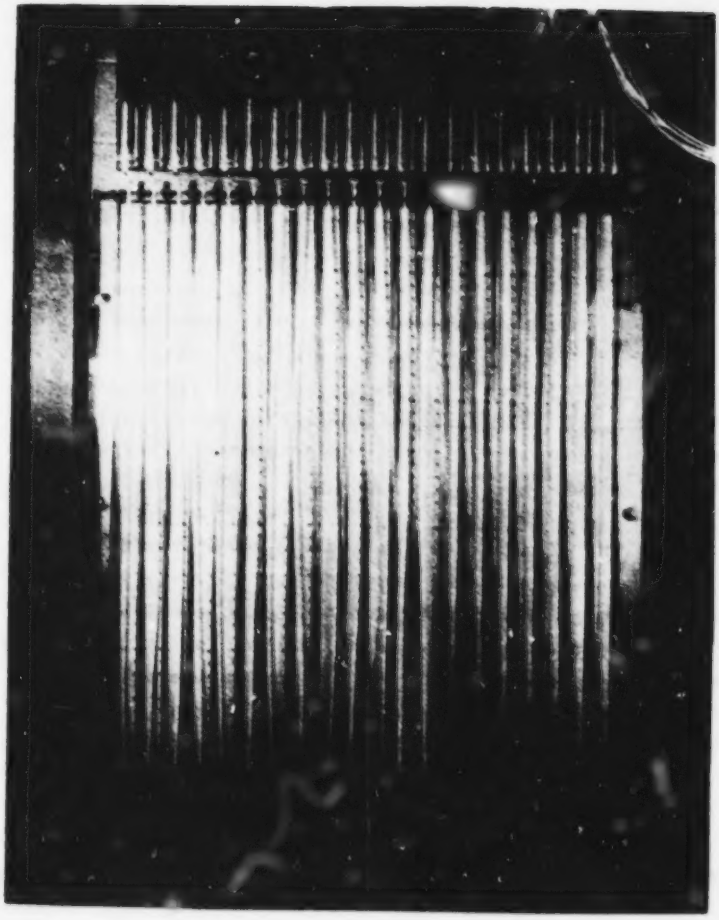


Fig. 12. Bank of manometers.

transducer is interfaced with the computer. The instrumentation for chemical analyses is described in Section 4 of this report.

3.2 Auxiliary equipment

3.2.1 The cyclone separator and flyash recycle system

The cyclone separator or flyash collector is a Joy 'MULTICLONE' containing two, 230-mm-diameter, vaned collection tubes operated in parallel. The cyclone separator is included in the photograph showing the upper sections of the combustor (Fig. 9). At low fluidization velocities dilution air is injected into the exhaust gas stream entering the separator to improve the collection efficiency. The maximum pressure drop across the collector is approximately 50 mm of water.

The flyash from the cyclone separator drains by gravity through a hopper and water-cooled pipe to a flow splitter where the flyash is directed to a collection drum or to an ejector for recycle to the bed, or is diverted, temporarily, to a sample tube for the determination of the flyash loadings. The channels of the flow splitter are connected in an inverted Y pattern with cooling water flowing through the space between the arms of the Y. The flyash is cooled as the particles slide along the cooled inside surface of the channel. A photograph of the flyash recycle system is shown in Fig. 13. The flyash is injected into the bed through an access port at the bottom of the bed. The air supply from the laboratory air line (550 kPa gauge) to the nozzle of the ejector is controlled manually by a throttle valve. The ejector and the recycle system have performed satisfactorily at flyash loadings up to 18 kg/hr.

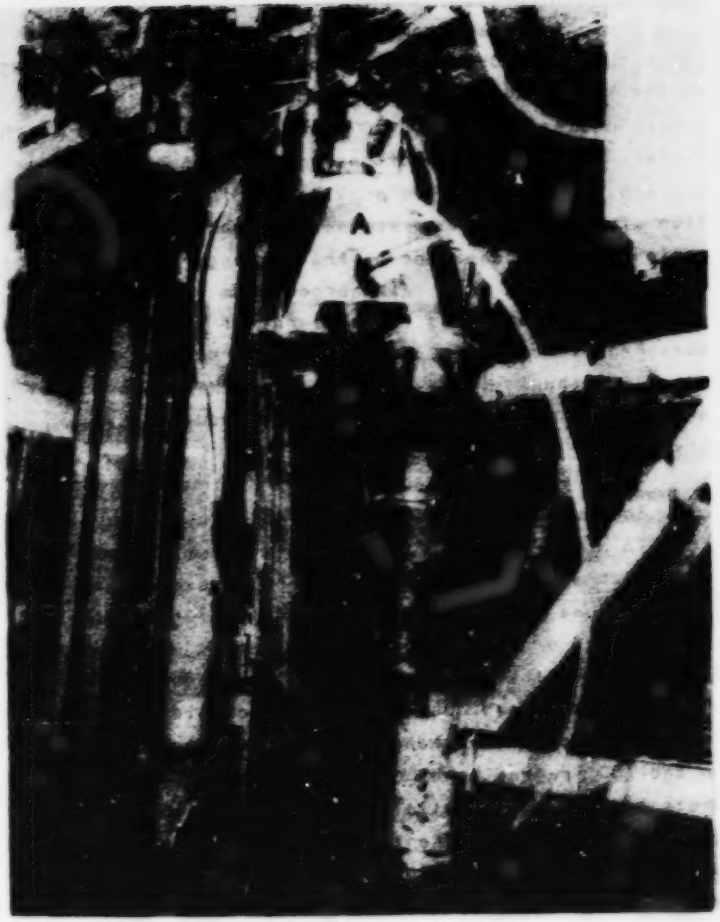


Fig. 13. Flyash recycle system (A, flow splitter; B, sample tube; C, ejector).

3.2.2 The exhaust gas heat exchanger

The gas stream from the cyclone separator is fed through a duct of 200-mm, stainless steel, 'BENDWAY' tubing to the shell side of the exhaust gas heat exchanger where the gas is cooled to the 150 °C operating temperature of the bag filter. The duct connections to the exchanger contain dampers and a bypass duct is provided so that all or any fraction of the flow may be bypassed around the exchanger. The coolant on the tube side of the exchanger is fresh city water or the cooling water discharged from the freeboard cooler. The flowrates and temperatures of the cooling water are measured by rotameters and Type T thermocouples as described for the in-bed exchanger. The inlet and outlet temperatures of the gas stream are measured with type K thermocouples.

The tube bundle consists of 48 U-tube bayonets attached to a 6.3-mm steel plate in a six-row, 51-mm triangular pitch arrangement. The U-tubes, assembled from 180° return bends and 610-mm lengths of 3/4-in standard steel pipe (I.D. 20.9 mm; O.D. 26.7 mm), are attached through holes drilled in the plate and sealed by pipe gaskets and nuts on the inside and couplings on the outside. Fig. 14 is a frontal view of the exchanger showing the tube retainer plate and 180° return bends connecting tubes of adjacent bayonets to give six parallel paths for the flow of coolant through the exchanger. The tube retainer plate is sealed by gaskets and bolted to the support frame of steel angle. The housing enclosing the tube bundle is 4.8-mm steel plate welded to the support frame. Removable panels on the top and back of the housing provide access to the shell for the removal of dust from the surface of the tubes. The tube assembly may be removed from the housing for refurbishing and replacing the tubes by unbolting the tube retainer plate from the frame and attaching the overhead hoist to hooks on

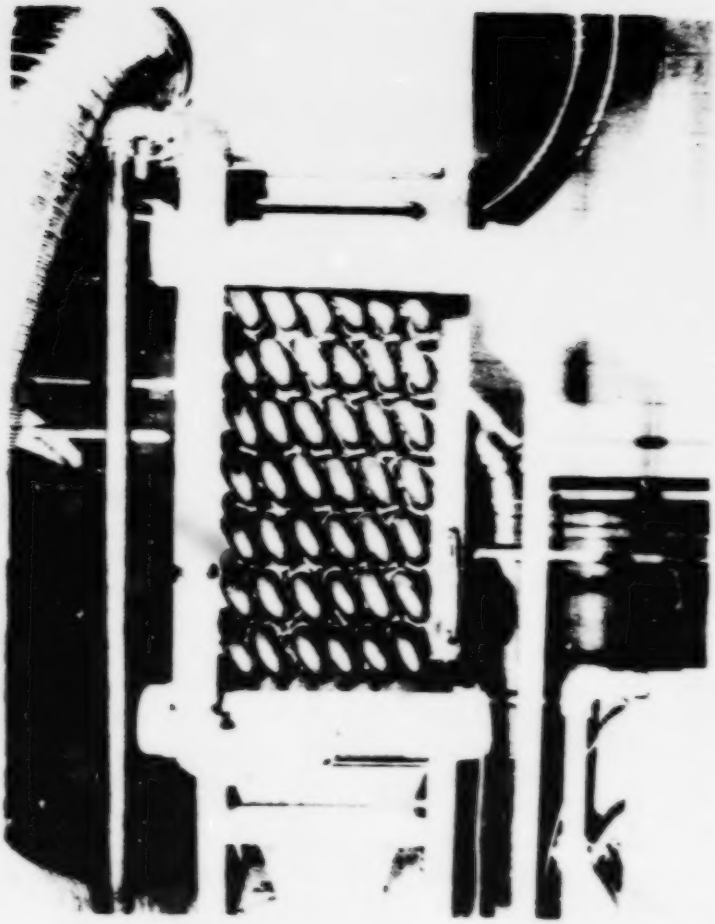


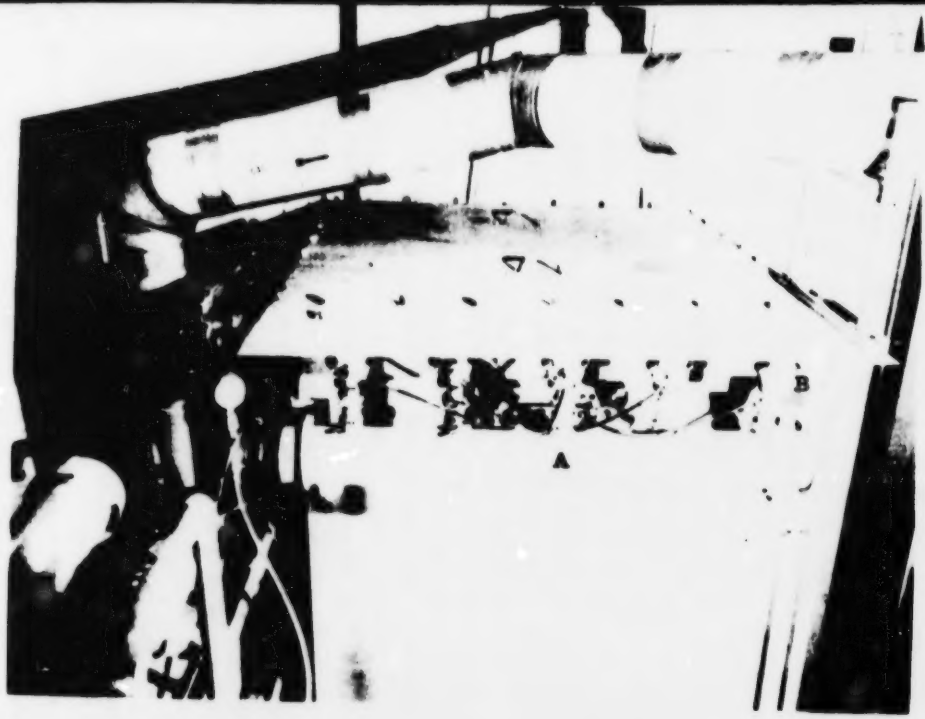
Fig. 14. Frontal view of the exhaust gas heat exchanger.

the outside of the plate. Handles have also been welded to the plate to aid in the manipulation of the tube bundle during the removal operation.

3.2.3 The bag filter

The cooled gas stream from the heat exchanger is fed to the bag filter where the dust remaining in suspension is removed before discharge to the stack. During startup of the combustor the filter is bypassed and the exhaust gases are fed directly to the stack. Once the temperature of the exhaust gases is under control, at the operating temperature of the filter, the flow is diverted through the filter.

The unit is an American Air Filter 'FABRI-PAK' filter containing 25 bags or tubes of 'NOMEX' fabric. The operating temperature is 150 °C with an upper limit of 200 °C. Prolonged operation above this limit damages the fabric. The capacity of the unit is 0.4 m^3/s at a pressure drop of 125 mm of water. The tubes are injected periodically with pulses of air from a bank of nozzles to discharge the layer of dust collected on the surface of the tubes. The solids discharged from the tubes collect in a hopper with a capacity of 0.15 m^3. The frequency of the pulses may be varied by adjusting the setting on a timer which activates solenoid valves on a compressed air reservoir. The reservoir or surge tank connected to the laboratory air line (550 kPa gauge) provides the capacitance required by the air-pulse system. Fig. 15 is a view of the top section of the housing of the bag filter showing the compressed air reservoir and bank of solenoid valves.



ig. 15. Top section of the bag filter (A, compressed air reservoir, B, solenoid valve).

3.2.4 The coal and limestone feed system

The coal and limestone are charged through a dump hopper, located in the second floor laboratory, to the two feed hoppers resting on the platforms of weigh scales on the mezzanine level of the pilot plant. The metered feed streams from the coal and limestone hoppers enter a relay hopper and are fed through a rotary, air-lock, star valve to an auger which discharges into the bed. The feed system may be operated in either overbed or underbed feed modes.

The coal and limestone feeders are 'BIF' (Basic In Flow) volumetric dry materials feeders with diaphragm agitation. The hoppers of the two feeders have capacities of 0.28 m^3. The metering screw on the coal feeder is a 3-in, stainless steel helix in a 3-in carbon steel spout giving a maximum feed rate of 0.16 m^3/hr at 7.6 rpm. The limestone feeder has a 3-in helical screw in a 3-in spout giving a maximum feed rate of 0.11 m^3/hr at 9.5 rpm. Both units are equipped with variable speed drives which are adjustable during operation. A photograph of the feeders is reproduced in Fig. 16. The feed rates of coal and limestone are determined from the weights of the feed hoppers which are continuously monitored by Toledo 'LECTROLEVER' platform scales. The scales are connected by cable to electronic indicators which have digital displays in increments of 0.2 kg. The scales are also interfaced with the computer.

The relay hopper is independently supported and connected to the spouts of the coal and limestone feeders by flexible rubber ducts. More reactive fuels may be introduced on a short-term basis through a port on the top of the relay hopper during the startup period.

Fig. 17 shows the feed auger attached to the combustor in the overbed feed mode. The casing of the auger

Fig. 16. Feed hoppers.

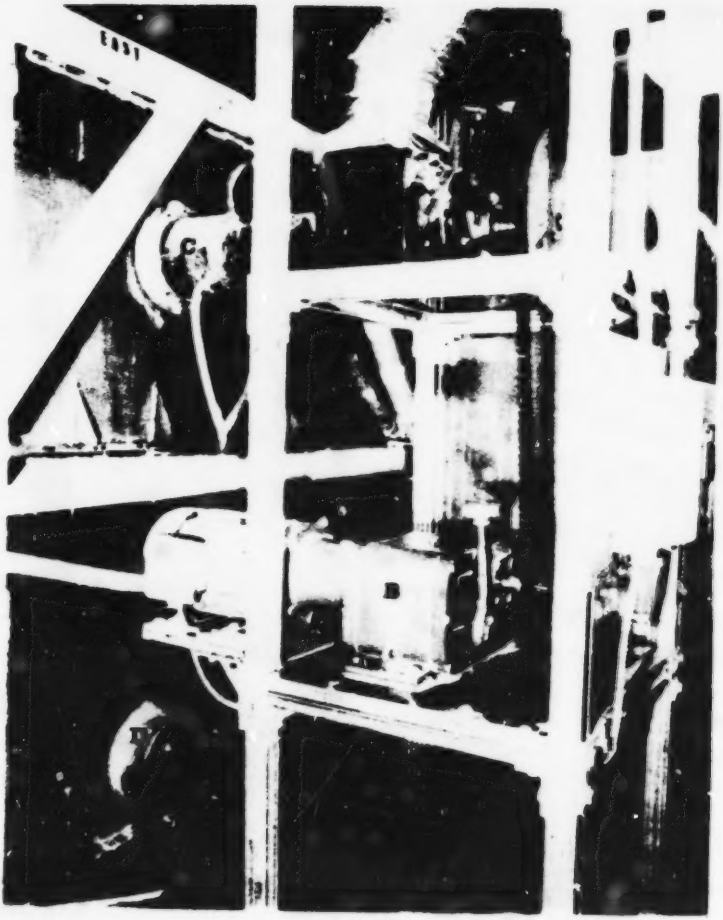


Fig. 17. Feed auger attached to the combustor in the overbed feed mode (A, auger; B, variable speed drive; C, water-cooled jacket; D, underbed feedport).

is 4-in standard steel pipe (I.D. 102.3 mm) and the screw has a standard pitch of one screw diameter (101.6 mm). The screw is driven through a variable speed, chain drive by a 1720-rpm, 1.1-kW electric motor. The auger has a water-cooled jacket on the discharge end and provision has been made for the injection of a water spray to moisten the feed mixture.

3.2.5 The lightup burner

The lightup burner is a model 4442S-6 'AARDVARK' burner made by North American Manufacturing Co. It is of the non-premix or "nozzle mixing" type in which fuel/air mixing and burning occur together, forming a turbulent diffusion flame. It has an exceptionally wide operating range, from stoichiometric air/fuel ratio up to 2000 % excess air. The corresponding temperature range of the product gas is roughly 1900--150 °C. The burner is very compact and the combustion intensity is correspondingly high. The alloy combustion chamber or "tile" is about 190 mm o.d. and 200 mm long, and necks down at the discharge to a 70 mm throat-diameter nozzle with standard 3-in pipe threading on the outside.

The burner was specified for propane/air operation, with a maximum thermal capacity or combustion heat release rate of 1.25×10^6 Btu/hr (367 kW). The propane in our installation is supplied from a tank at 40 psig (276 kPa gauge pressure) and is then reduced by a controlled-pressure reducing valve. Air is supplied by a Roots blower providing a maximum delivery pressure of 5 psig (34.5 kPa gauge). The burner control and safety system was engineered by North American Manufacturing Co. Ignition is by a spark plug and flame supervision is through a UV detector. We have mounted the burner and its systems on a rack on wheels, Fig. 18-20, so it forms a compact, integrated whole and can be easily

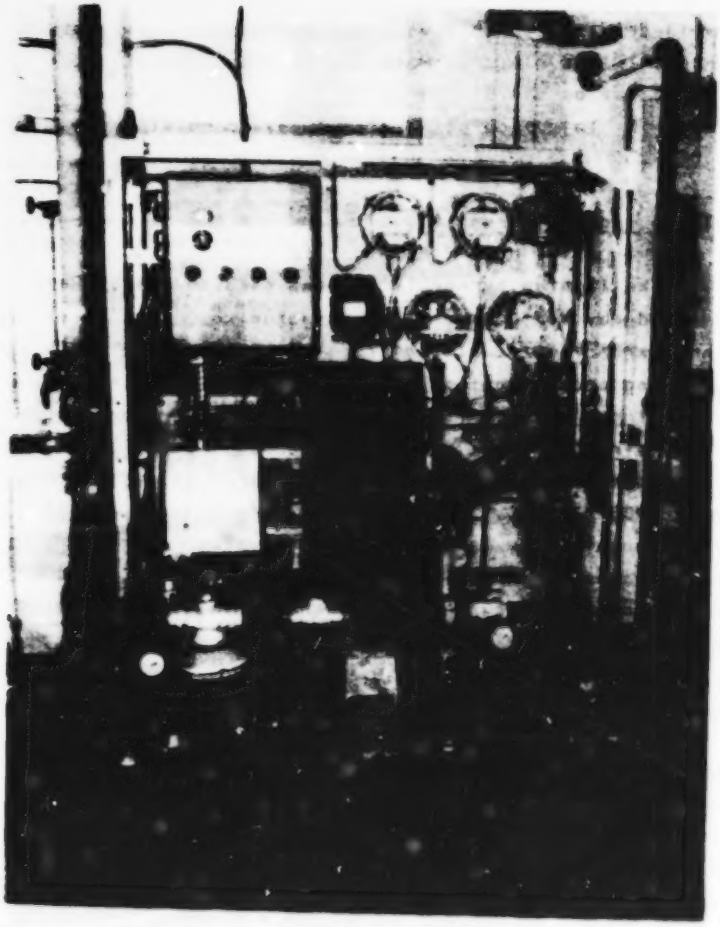


Fig. 18. Rear view of lightup burner.

Fig. 19. Frontal view of lightup burner.

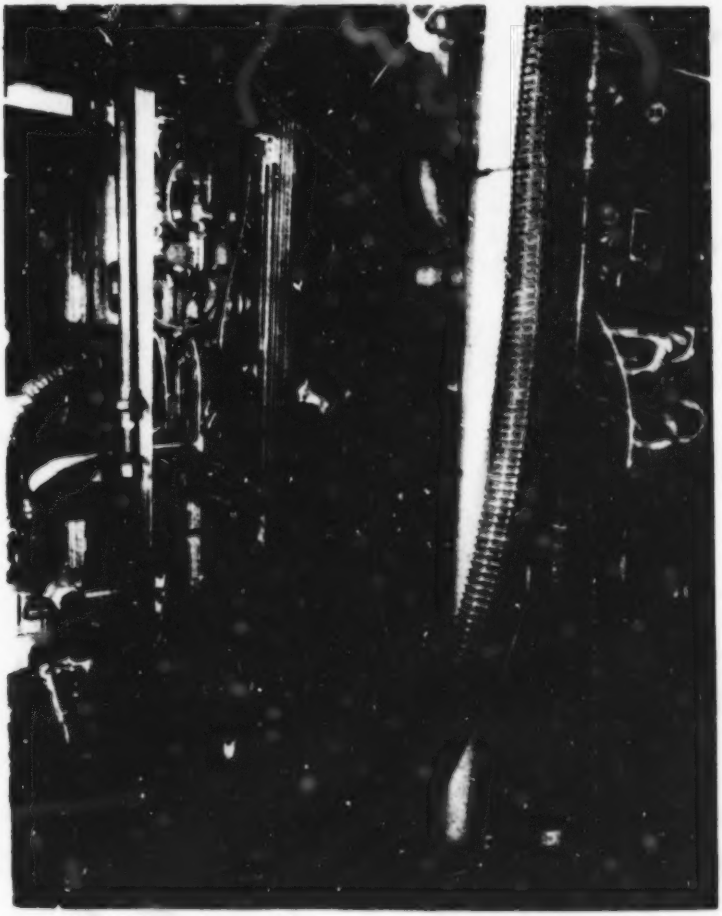


Fig. 20. Lightup burner in position for firing.

moved in and out of the pilot-plant room, and easily connected to and disconnected from the FBC combustor. The burner is spring-mounted to ease connection and to diminish stress at the joint.

A screwed flange (3-inch standard pipe thread) is fitted to the burner discharge nozzle and is, in operation, attached to a corresponding flange on the light-up burner gas-intake port in the side of the combustor. This port is located just above the distributor plate, Fig. 11. The part of the port which is integral with the combustor (welded in) is a 154 mm i.d. mild steel tube set in the wall of the combustor. To protect this tube from the high-temperature lightup gas, the gas actually travels the port through a 140 mm o.d. inner tube made of Type 310 stainless steel lined on the inside with high-temperature baked-in refractory tapered from 76 mm i.d. at the intake end to 102 mm i.d. at discharge. A flow of cold air through the annulus between outer and inner tubes, into the combustor, provides the required cooling.

The lightup burner system is connected to the gas and air supplies with quick-disconnect couplings. The flange attachment to the combustor is with two bolts. In practice, when the combustor has reached operating temperature the fluid bed is slumped (air supply is shut off). The burner is stopped and disconnected, and a blind flange is attached over the light-up port in the combustor. The FBC operation is then restarted and the burner system is moved out of the room. The loss in bed temperature incurred during the slump period is typically 50 °C.

3.2.6 The air blowers

The air for combustion and fluidization is supplied by two Roots, rotary lobe, positive displacement blowers

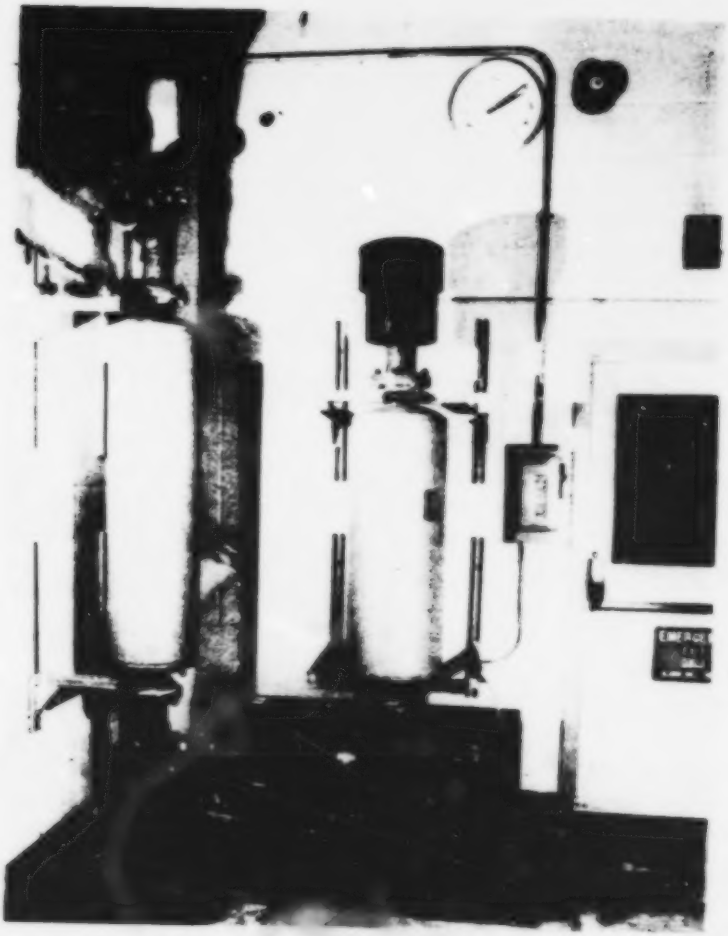


Fig. 21. Roots air blower.

equipped with inlet and outlet silencers and pressure relief valves. One unit, Model 59AF (Canadian Air Compressor Limited), has a capacity of 0.16 m^3/s at 1300 rpm and a delivery pressure of 24 kPa gauge. The other unit, Model 3509-J (Canadian Air Compressor Limited), has a capacity of 0.08 m^3/s at a delivery pressure of 34 kPa gauge. Both units are driven by 5.6 kW, 1800 rpm, electric motors through variable speed drives. A photograph of the Model 3509-J blower is shown in Fig. 21. The Model 59AF blower has sufficient capacity for the operation of the combustor at low and intermediate fluidization velocities. The combined outputs of both units are required for operation at high fluidization velocities and for the cold model work.

4. INSTRUMENTATION AND SAMPLING PROCEDURES FOR THE FLUIDIZED BED COMBUSTOR (FBC) (M. Couturier)

4.1 Introduction

The FBC at Queen's University is a research facility and as such is only useful if measurements on its various input and output streams can be made. To determine the performance of the combustor, the only samples required for compositional analysis are those taken on the gas and solid streams entering or leaving the combustor. However, if one is to determine the mechanics of combustion and sulphur capture in a FBC, the same or similar sample analysis must also be performed on the high-temperature, solids-gas mixtures which exist in the fluidized bed.

4.2 Sampling locations

There are seven areas of the FBC that require compositional analysis:

- Input stream

- o furnace outlet
- o cyclone gas outlet
- o recycle
- o ash overflow
- o fluidized bed
- o freeboard

Characterization of the streams at each of these sample points will permit a material balance around the FBC and should also provide the information needed to understand the mechanics of fluidized bed combustion and sulphur capture. The following problem is common to all areas: obtaining a representative sample. Each area will now be described together with the instrumentation required.

4.3 Input streams

4.3.1 Air

The incoming air will only be analyzed for its moisture content. The combustion air is taken from inside the building containing the FBC facility and its moisture content can easily be determined with a sling psychrometer.

4.3.2 Coal and limestone

The required measurements to be taken on the coal and limestone feed are listed in Table 1.

Before being fed to the combustor, each barrel of coal or limestone is mixed in a rotary mixer and a sample is taken as the mixer is emptied. The particle size distribution is then obtained using a series of Tyler screens. The samples are then pulverized and sub-samples are taken for analysis.

Table 1

Required Coal and Limestone Measurements

Coal	Limestone
Particle Size Distribution	Particle Size Distribution
Approximate Analysis	wt % Carbon Dioxide
wt % Hydrogen	wt % Calcium Oxide
wt % Nitrogen	wt % Magnesium Oxide
wt % Sulphur	wt % Trace Elements
wt % Carbon	
Heating value (cal/g)	

The proximate analysis of the coal is performed using the Fisher Model 490 Coal Analyzer. This analyzer is compact, can handle 80 samples simultaneously and the results are generally obtained in one working day. The proximate analysis yields the % free moisture, % volatiles, % ash and % fixed carbon of the coal.

The sulphur content of the coal is determined using the Fisher Model 475 Sulfur Analyzer. The analysis is totally automated and takes approximately five minutes per sample. Basic system operation involves combustion in a tube furnace at 1350 °C of a pre-weighed sample in the presence of pure oxygen. Available sulphur compounds are oxidized and exit the furnace into a solvent-filled reaction vessel. The resulting mixture is titrated automatically and a microprocessor calculates the % sulfur using the volume of titrant dispensed, the sample weight and the titrant factor.

The carbon, hydrogen and nitrogen content of the coal is measured with a Hewlett-Packard Model 185 CHN analyzer. The sample elements are first converted to the

desired oxidation states (N_2, CO_2 and H_2O) in the presence of an oxidant at high temperature and the products of combustion are then analyzed by a gas chromatograph. The nitrogen, carbon dioxide and water peaks are used to calculate respectively the amount of nitrogen, carbon and hydrogen in the coal sample.

The heating value of the coal is determined with an oxygen bomb calorimeter made by Parr Instrument Company.

The chemical composition of the limestone is determined by standard wet chemical analysis. The carbon dioxide content of the limestone can quickly be estimated by measuring the difference in weight after calcining the sample at high temperature.

4.4 Solid sampling

All solid samples taken within the FBC or in the leaving streams are analyzed for particle size distribution and chemical composition using the instruments described in section 4.3.2.

4.4.1 Recycle

The solids leaving the bottom of the cyclone can be sampled by means of a diverting valve. The valve can be used to direct the solids flow to the furnace or to a sample container. The recycling rate can also be determined in this way by measuring the time required to fill the sample container.

4.4.2 Ash overflow

An instantaneous sample of the material leaving the bed can easily be taken at the cooled-auger outlet. Also,

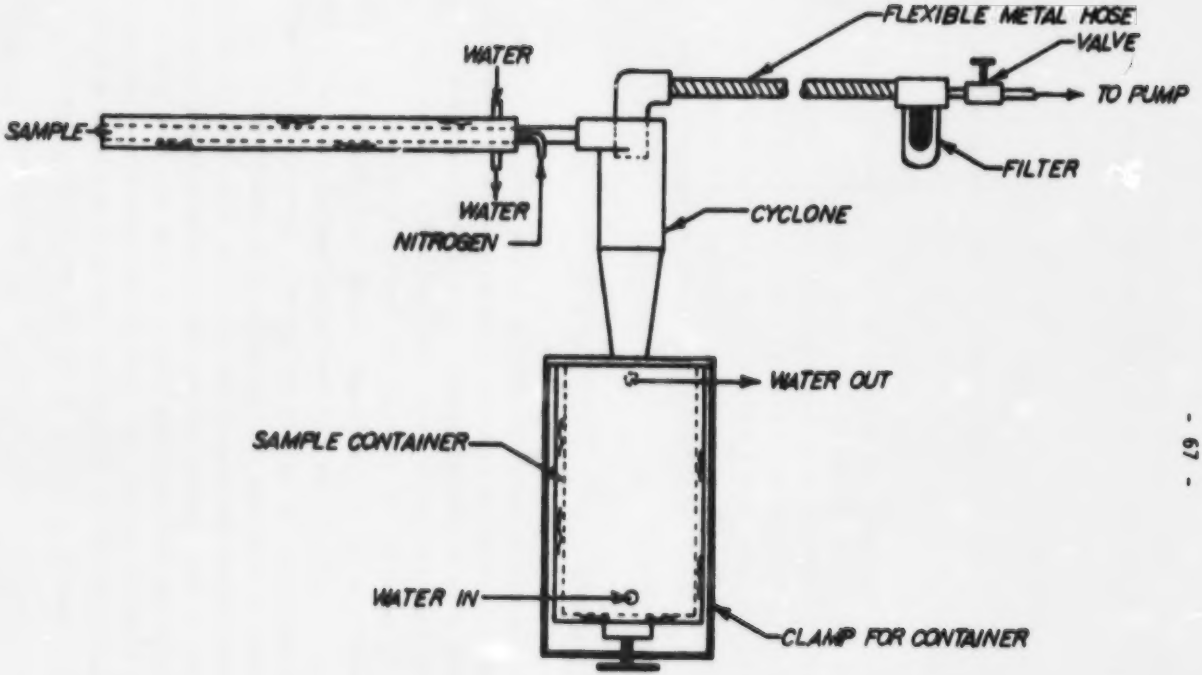


Fig. 22. In-bed solids sampling system.

an integrated sample can be obtained by mixing the total product collected during a run and taking a sample of the mixture.

4.4.3 Fluidized bed

The system used for taking solids samples within the fluidized bed is shown in Fig. 22. A water-cooled probe is inserted inside the bed. The sample enters the tip of the probe and is pneumatically conveyed to the cyclone by the nitrogen stream injected at the probe tip. The cold nitrogen stream also quenches the high temperature reactions and prevents further oxidation of the coal. The solids sample is collected in a water-cooled stainless steel container and the gases after being filtered exit through a pump. It usually takes about 2 minutes to collect a one liter solid sample.

4.4.4 Freeboard

The system used for taking solids samples in the freeboard is shown in Fig. 23. The sample is obtained by inserting a water-cooled probe into the freeboard and sampling isokinetically (i.e., the velocity through the probe tip matches the average gas velocity in the freeboard). A metered nitrogen stream is injected at the probe tip to quench the gas reactions and also to carry the solids sample to the solids collector. The solids collector is located at the rear of the probe in a compartment maintained above the sample dew point by the circulation of hot water. The leaving gas stream is carefully metered and by subtracting the nitrogen flowrate from it, the true sample flowrate can be obtained. This system can collect a representative solids sample for analysis and also provide the dust loading in grams of solids per gram of air.

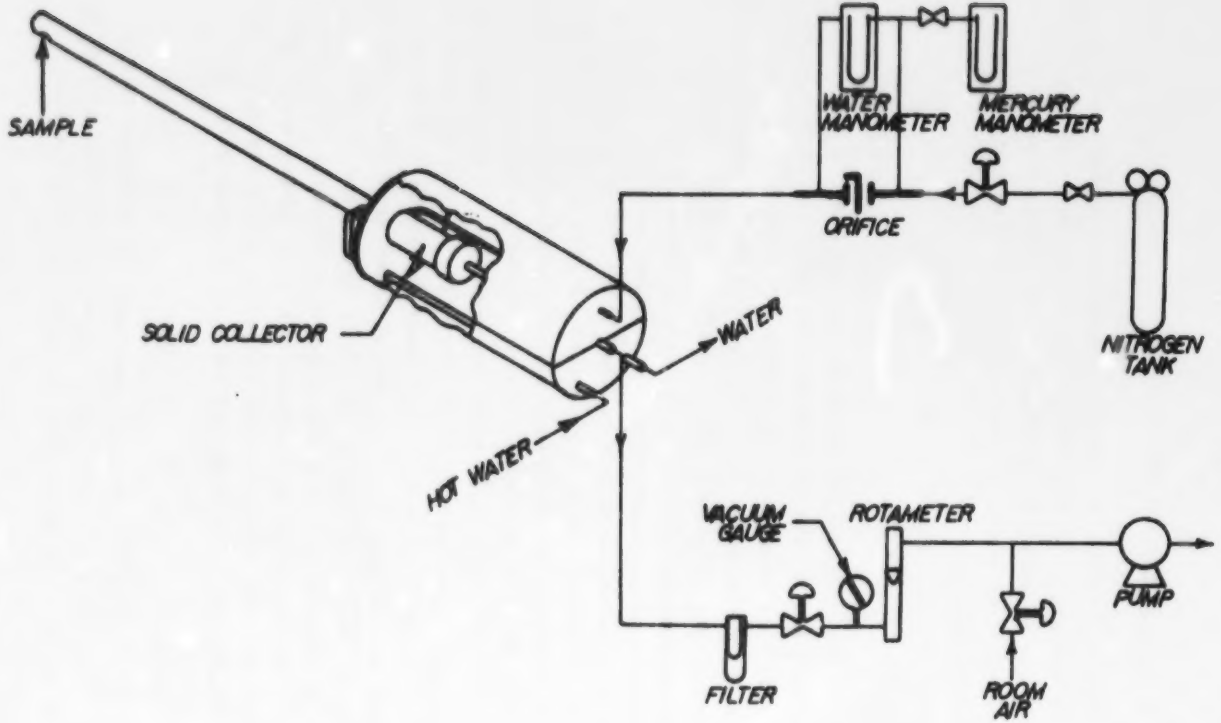


Fig. 23. Freeboard solids sampling system

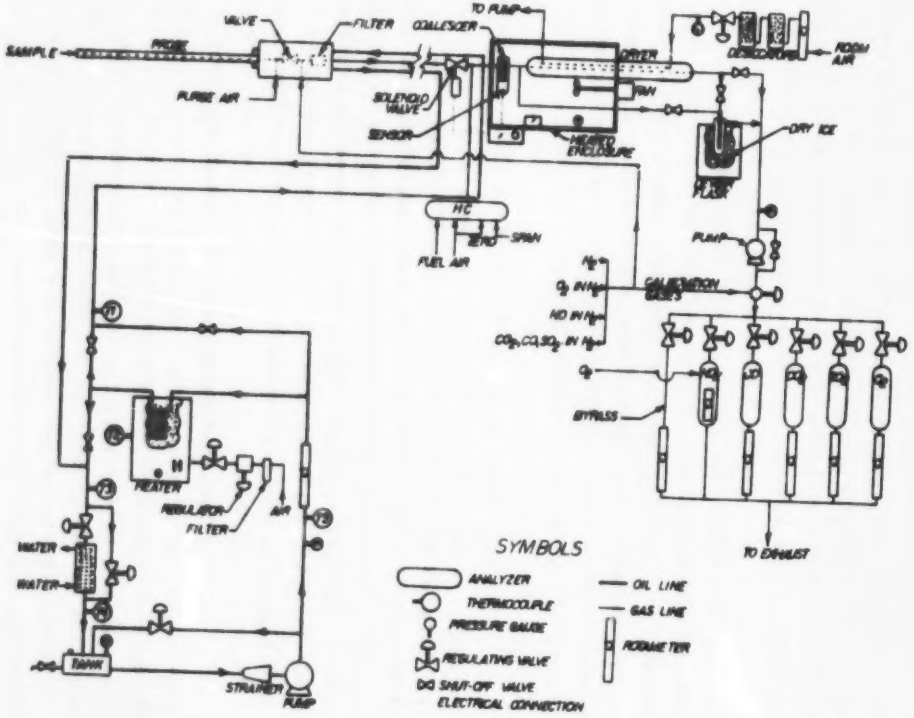
4.4.5 Cyclone gas outlet

The cyclone gas outlet can be sampled with the system described in section 4.4.4. Also, an integrated sample can be obtained by cleaning the baghouse very carefully after each run and taking a sample from the collected solids.

4.5 Gas sampling

Gas samples are taken within the bed, in the freeboard and at the furnace outlet. The gas streams are analyzed continuously for O_2, H_2O, NO_x, CO, CO_2, SO_2 and hydrocarbon content. Nitric oxide and the total oxides of nitrogen ($NO + NO_2$) are measured with the Model 10A Chemiluminescent $NO - NO_x$ Gas Analyzer made by the Thermo-Electron Corporation. The oxygen content of the gas sample is measured with a Beckman Model 755 Paramagnetic Oxygen Analyzer. Also, the concentrations of CO, CO_2 and O_2 are measured with infrared Analyzers manufactured by Beckman and the total hydrocarbon content of the gas sample is measured with a Beckman Model 402 Hydrocarbon Analyzer. The hydrocarbon analyzer utilizes the flame ionization method of detection and its output, expressed in ppm CH_4, is proportional to the rate at which carbon atoms enter the analyzer. Finally, the water concentration is determined by passing the gas stream into a pre-weighed trap immersed in dry ice. The flowrate of the gas stream, the time during which condensation took place and the weight of collected water are carefully monitored and used to calculate the water concentration.

The system used for gas sampling is shown in Fig. 24. The probe and sampling lines are maintained at 160 °C by a hot oil system so that no water, sulfuric acid or



F'g. 24. Gas sampling system.

hydrocarbons can condense. A filter is installed at the tip of the probe to prevent the large particles from entering the probe and air is available to back-purge the filter when it clogs up. The smaller particles that pass through the first filter are removed by a second filter at the back of the probe.

After leaving the probe, part of the gas sample is transported to the hydrocarbon analyzer and the remainder of the sample enters a heated enclosure maintained at 60 °C. This temperature is below the acid and hydrocarbon dew point and any acid or hydrocarbon droplets are thus trapped in the coalescer located in the heated enclosure. The gas stream is then dried to a dew point of -18 °C using a semi-permeable membrane sold by Perma Pure Products Inc. Also, in the event of an oil leak into the gas line, a sensor located in the coalescer will detect the presence of the oil and a solenoid valve will automatically close, preventing any oil from entering the gas analysis system.

The SO_2 analyzer is very sensitive to water content and when its most sensitive range is used, a condensing trap must be used after the Perma Pure dryer to lower the dew point even further. The dry ice trap lowers the dew point to -78 °C and can also be used to determine the water content of the gas stream by bypassing the Perma Pure dryer. After the gas sample has been dried, it goes through a diaphragm pump and is then divided amongst the analyzers.

The calibration gases are introduced before the instruments or at the probe. Calibration gases are introduced at the back of the probe to check if there is any interference in the sampling system. To prevent interference due to gas adsorption or chemical reaction, all lines in contact with the gas sample are made of tefion and all fittings are made of stainless steel.

5. ACQUISITION AND PROCESSING OF EXPERIMENTAL DATA (F. Preto)

The AFBC pilot plant is supported by an instrumentation system designed to provide complete monitoring of operating conditions, and allow for data reduction during a run. This is illustrated in Fig. 25. At the heart of the system is an HP9836A computer which receives data from scanners, instruments, and processors, reduces the data, displays desired parameters, and stores data on disc. The system also has the capability of providing hardcopy tables and graphs.

The HP9836A features a 16 bit microprocessor (Motorola 68000), 298K bytes of user read/write memory, dual 5.25-in disc drives, and Serial, GPIO, and HP-IB interfaces. Programming is done in the BASIC computer language. The computer has a 12-in screen with full graphics capabilities, allowing display of data on process flowsheets. Data may also be displayed in graphical form, thus allowing for continuous monitoring of operating trends.

The HP-IB and GPIO interfaces allow hardcopy reproduction of data or display on plotter and printer, respectively. The Serial interface allows hookup of the HP9836A to an Omega thermocouple scanner. This unit reads 30 type T or K thermocouples, digitizes the voltages, linearizes, and transmits actual temperature values to the HP9836A. The Omega scanner can also be operated without a computer, with temperatures displayed on a terminal.

The HP-IB interface also connects the computer to an HP2240A Measurement and Control Processor. The HP2240A contains A/D and Digital I/O boards. The A/D converter digitizes voltages from the various on-stream analyzers: CO, CO_2, NO_x, O_2, SO_x, and HC. The readings are then passed

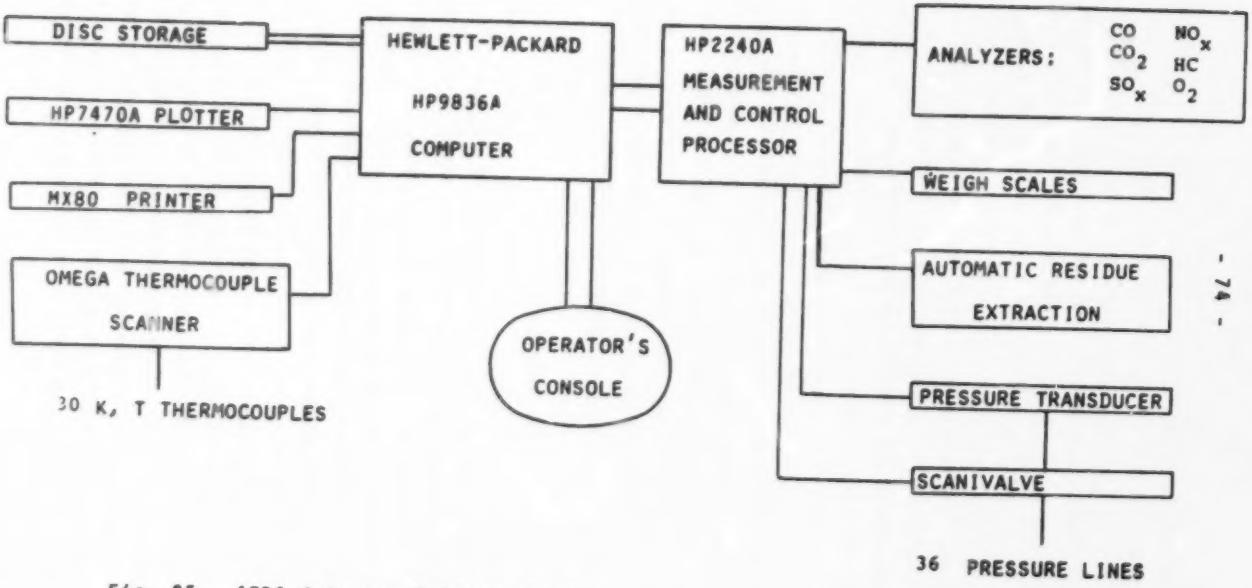


Fig. 25. AFBC data acquisition system

on to the HP9836A, which carries out the necessary linearization and reduction. The A/D converter also receives signals from a single pressure transducer. The system requires only a single transducer due to the use of a 36-channel Scanivalve pressure scanner, which connects one pressure line, at a time, to the transducer. The Scanivalve can be run manually, or by using the digital output of the HP2240A. Using pressure drop data, the computer estimates gas flow rates, and bed height, and through digital output controls a residue extraction system to maintain a desired bed level. The digital inputs of the HP2240A monitor the coal and limestone weigh scales.

Using information from all of the above, the computer performs the routine material and energy balances. The computer also has the capability of carrying out spectral analyses of pressure fluctuations and species concentrations, and mathematical modelling as an aid to selection of operating conditions.

6. CONCLUSION

The pilot plant is now in operation. The initial construction phase is done and further developments will take the form of evolutionary modifications and improvements and the replacement of obsolete or worn-out subsystems and components. We have already mentioned the replacement of the PDP11/10 minicomputer by a Hewlett-Packard Model HP9836A desktop computer which is underway. Another change is the development of accurate temperature probes for determining freeboard gas temperatures; the bulky fixed probes now in place, although in use by virtually everyone working in the field, simply cannot be relied upon (because they clearly respond to radiant flux, not gas temperature).

A few design features whose significance is not

explicitly mentioned in the above detailed discussion should be noted:

- The freeboard space is of the same cross-section, and is continuous with, the fluid bed; there is no expansion in cross-section as is seen in some installations. This means that the freeboard gas is essentially in "plug flow", so data on gas composition, velocity and temperature can be easily interpreted kinetically.

- The pneumatic cyclone dust recycle is driven entirely by an air jet ejector. This has so far worked excellently. Entrainment of exhaust gas from the cyclone has been reasonably small and has not interfered with proper cyclone operation. The ejector, of course, must be properly sized and shaped for the operation.

- The in-bed cooling tubes are not all run in parallel, but in series/parallel combinations. Normally the tubes at a given level in the bed, or even at two adjacent levels, are connected in series. The heat transfer coefficient measured is thus an average for all the tubes in a series circuit. The rationale is that variations in the coefficient with vertical position in the bed are expected to be much larger than horizontal variations, and the latter should in fact be practically unimportant.

- Although the system is presently set up for feeding coal and limestone to the bed by means of a screw conveyor, this mode has been chosen simply because of a plan to include relatively large particle-sizes of coal in the initial programs (up to 50 mm). When interest is restricted to suitably small particles (say less than 5 mm dia.), pneumatic feeding can easily

be substituted. The screw conveyor following the air-lock star feeder is simply removed and a pneumatic injection system is put in its place.

Finally, it may be noted that the pilot plant work which is facilitated by the installation described herein is being complemented by a variety of parallel studies in our laboratories:

- Cold-modelling studies of fluidization dynamics, heat transfer, mass transfer, and elutriation
- Bench-scale studies of combustion and SO_2 capture, using (a) thermogravimetric analysis (TGA), and (b) a bench-scale fluid-bed reactor
- Mathematical modelling studies (mathematical simulation of combustor performance).

ACKNOWLEDGEMENTS

The collaboration and support of scientists at the Energy Research Laboratories (CANMET, Energy, Mines and Resources Canada) is gratefully acknowledged, particularly from Mr. Stefan Steindl who did the detailed design work on the combustor after the basic principles had been decided by group discussion, Dr. Ben Anthony who as Scientific Authority was unfailingly helpful and concerned, and Mr. Frank Friedrich and Mr. George Lee whose experience and advice were most critical in the early stages of the work. Special recognition is also deserved by our Ph.D. students Mr. Michel Couturier and Mr. Fernando Preto who might have chosen faster routes to a degree than one involving a lengthy construction project but who gave it their enthusiastic support and made some very substantial and invaluable contributions. Lastly, we acknowledge the contribution of the technicians in the shops of the Department of Chemical Engineering at Queen's University who very competently carried

out much of the construction work and gave useful advice on design problems; they are Mr. Charles Bullock, Mr. James Duncan, Mr. William Hutcheson, and Mr. George Raynes.

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